Escola d'Enginyeria de Telecomunicació i Aeroespacial de Castelldefels
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FINAL DEGREE THESIS

TÍTOL DEL TFG: Analysis of different mechanical properties of composites and design of a hands-on activity for Bachelor's degree

TITULACIÓ: Grau en Enginyeria d'Aeronavegació

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Resumen

Incluso aunque el mercado aeroespacial solo sea alrededor del 1% del mercado total de materiales compuestos, estos materiales siguen siendo muy importantes para toda la industria debido a su imagen de alta tecnología y los desarrollos tecnológicos que continúan surgiendo, siendo la industria aeroespacial el mayor consumidor. En la industria aeroespacial, los materiales compuestos de fibra de carbono se han utilizado para fabricar las carcasas de los motores de cohetes, los tubos de lanzamiento desde los que se disparan los misiles, la carcasa del motor de misiles, muchos componentes de las estructuras de las aeronaves, etc. Además, algunos vehículos espaciales, como el transbordador espacial, usa compuestos de carbono-carbono cuando la resistencia al calor es crítica para su rendimiento.

Al principio, los compuestos de fibra de carbono se utilizaron en algunos componentes no críticos de las aeronaves, como puertas de acceso y los capós de motores. Los aviones militares adoptaron componentes de fibra de carbono más rápidamente que los aviones comerciales como el F-16 o el F-18. La mayoría de las palas de los helicópteros están hechas de fibra de vidrio o combinaciones de fibra de vidrio y fibra de carbono y muchos de los fuselajes de muchos helicópteros también están hecho de materiales compuestos.

En detalle, los objetivos principales de esta tesis son: 1) el estudio de los materiales compuestos para adquirir conocimiento para entender los resultados experimentales y numéricos; 2) fabricar las muestras de materiales compuestos y probar experimentalmente las muestras resultantes con el equipo apropiado y simular estas muestras a través de un software apropiado; 3) analizar los resultados experimentales y analíticos y confirmar qué material tiene mejores propiedades mecánicas; 4) realizar diferentes actividades prácticas para futuros estudiantes de Ciencia y Tecnología de los Materiales (CTM), una asignatura de segundo grado de la carrera universitaria en Ingeniería Aeroespacial.

A través del estudio experimental y numérico de esta tesis, se puede confirmar que las muestras de fibra de carbono tienen mejores propiedades mecánicas que las muestras de fibra de vidrio. En particular, la rigidez y la máxima resistencia a la tracción de las muestras de fibra de carbono es significativamente mayor que la resistencia de las muestras de fibra de vidrio. Por lo contrario, las muestras de fibra de vidrio poseen más ductilidad, ya que pueden absorber más energía de deformación que las muestras de fibra de carbono.

A través de la realización de este proyecto, se puede confirmar que, debido a los requisitos de la industria aeroespacial, el uso de materiales compuestos de fibra de carbono para aplicaciones aeroespaciales predomina sobre los materiales compuestos de fibra de vidrio, si el coste es secundario, ya que los materiales compuestos de fibra de carbono tienen mejores resultados que se adaptan mejor a la mayoría de las aplicaciones de esta gran industria. Por lo tanto, es importante que los estudiantes del grado en Ingeniería Aeroespacial obtengan valiosos conocimientos sobre estos materiales mediante, por ejemplo, las actividades prácticas propuestas en este trabajo.

Abstract

Even though the aerospace market is only about 1% of the total composites market, it remains highly important for the entire composites industry because of its high-tech image and the associated technological developments. In the aerospace industry, carbon-fiber composites have been used to make the casings of rocket motors, the launch tubes from which the missiles are fired, the missile motor housing, many components of the aircraft airframes, etc. Moreover, some space vehicles, such as the space shuttle, use carbon-carbon composites when the heat resistance is critical to its performance.

At first, carbon-fiber composites were used in some non-critical components of aircraft, such as access doors and engine cowlings. Military aircraft adopted carbon-fiber composites earlier than commercial aircraft due to the lower safety requirements, like the F-16 or F-18. Aircraft like the B-2 and F-22 are entirely made of composites. Most helicopter blades are made of fiberglass or combinations of fiberglass and carbon-fiber, and the fuselage of many helicopters is also made of composites.

In detail, the main goals of this thesis are: 1) study the basis of composite materials in order to understand the experimental and numerical results; 2) fabricate composite samples and test experimentally these samples with appropriate equipment, and simulate these samples through appropriate software; 3) analyze the experimental and model results and confirm which material has better mechanical properties; and 4) design hands-on activities for future students of Science and Technology of Materials (CTM), a 2nd grade subject of the Bacherlor's degree in Aerospace Engineering.

Through the experimental and numerical study of this thesis, it can be confirmed that carbon-fiber samples have better mechanical properties than glass-fiber samples. Particularly, the stiffness and the ultimate tensile strength of the carbon-fiber samples is significantly higher than those of the glass-fiber samples. On the contrary, glass-fiber samples exhibit more ductility as they can absorb more deformation energy than carbon-fiber samples.

After the realization of this project, it can be confirmed that, due to the aerospace industry requirements, the use of carbon-fiber composites for aerospace applications predominates over glass-fiber composites, if the cost is secondary, as carbon-fiber composites have better mechanical properties that fit better most applications in this large industry. Thus, it is important that students of the Bacherlor's degree in Aerospace Engineering gain valuable knowledge on these materials by means of, for instance, the hands-on activities proposed in this work.

Aquest projecte el dedico, especialment, als meus co-directors, ja que sense la seva ajuda no hauria estat possible.

També vull dedicar aquest projecte als meus familiars i amics, per haver-me acompanyat durant aquest camí.

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INTRODUCTION

Materials are probably more deep-rooted in our culture than most of us realize. In our day to day we are constantly in contact with a lot of different materials. Historically, the evolution of materials has been driven by economics, logistics, and the expectations of society. Evolution has been facilitated by our abilities to produce, understand, and manipulate materials to fill our needs. In fact, early civilizations have been designated by the level of their materials development: Stone Age, Bronze Age and, Iron Age.

Our greatest interest for the realization of this work is focused on composite materials in aerospace industry, specifically, materials engineering, which is based on these structure-property correlations, designing or engineering the structure of a material to produce a predetermined set of properties.

Forty years ago, aerospace industry was dominated by aluminum because it was considered lightweight, strong, stiff, and resistant to fracture. In fact, as much as 70% of an aircraft was once made of aluminum. Nowadays, aircraft's structures have changed. Today, a typical aircraft is 20% pure aluminum. Most of the non-critical structural materials are composite materials.

There is a revolution underway in commercial aircraft manufacturing today and it can be summed up in one word: *composites*.

Composites have been in use for thousands of years: houses made of mud and straw, cloths made of animal skins/furs, etc. They also occur naturally in human and animal bones, wood structures, etc.

The first composites that were used in the aerospace industry were during World War II. Now, there are a lot of private jets and modern commercial aircrafts that use composites. These materials can be considered the future of this industry without devaluing other materials that are still in use today.

After having seen the current situation and the near future, it could be said that every year aircraft manufacturing companies use a higher proportion of composite materials in the construction of each new generation of aircraft. Composites on the Boeing B787 account for 50% of the aircraft's structural weight and composites make up about 52% of the total airframe of the Airbus A350. This is a fact that highlights the importance of these materials in the current aeronautical sector.

The aim of this thesis is to analyze the mechanical properties under static loading conditions (e.g., yield stress, tensile stress, Young's modulus) of various types of composite materials.

This project is divided in three main blocks. The objective of the first block is to provide an extensive introduction on composite materials in relation to the aerospace sector. This section establishes which elements are essential to perform a suitable laminate and presents the manufacturing processes of laminated composites that are currently being applied. Moreover, it will be also described the use of composite materials in the aerospace industry. Indeed, the story line of these materials is analyzed from its first applications to its current use.

In the second block, different composite samples will be prepared having all epoxy resin as matrix and with reinforcement made of carbon or glass fibers. Then, these samples will be tested experimentally in appropriate equipment: a universal testing machine (UTM). Finally, these samples will be simulated through an appropriate software, *Abaqus CAE*, and the results will be compared.

Finally, in the last part, different hands-on activities will be performed with educational purposes based on the acquired experience. These hands-on activities will be made thinking on the students who course the subject Science and Technology of Materials (CTM). Through this hands-on activity students will be able to grow their minds and learn based on the experience and the environment they will be exposed to.

CHAPTER 1. COMPOSITES IN AEROSPACE INDUSTRY

1.1. Typical materials used in aerospace industry

1.1.1. History of composite materials

The history of modern composites probably began in 1937 when salesman from the Owens-Corning Fiberglass Company began to sell fiberglass to interested parties around the United States. Those customers found that the fiberglass could serve as a reinforcement and soon realized that the aircraft industry was a likely customer for this new type of material. Other applications in tooling for aircraft soon followed as molds, jigs, and fixtures.

During World War II, the use of composites increased. A great number of aircrafts were developed and, consequently, the manufacture of the tooling needed to create new aircrafts increased too. In addition, the use of composites was extended to make structural and semi-structural parts of the airplanes.

Composite applications included ducts, engine nacelles (covers), radomes (domes to protect aircraft radar antennas), a structural wing box for the PT-19 airplane, and thousands of other applications.

Summarizing, composites materials have been used in the aerospace industry for many decades, initially in non-safety critical applications and more recently as primary structures, including fuselage and wing structures on the latest aircraft from Boeing, Airbus and Bombardier.

Development of composites of aerospace use was both costly and potentially risky. Therefore, initial development was performed by military that had relatively large development budgets and are not so risk as the civil side. On the civil side, composite development was restricted to non-structural applications.

When the civilian aircraft industry had to respond to the rising cost of oil and pressures due to environmental concerns composite materials were the ideal candidate. The more lightweight aircraft structures that result from substituting composite for metal have lower fuel costs and reduced emissions.

An ever-growing aerospace market presents major opportunities to the composites sector to develop products and technologies for current and future platforms, with the capability of composite materials becoming more advanced and suited to applications across the entire aircraft environment.

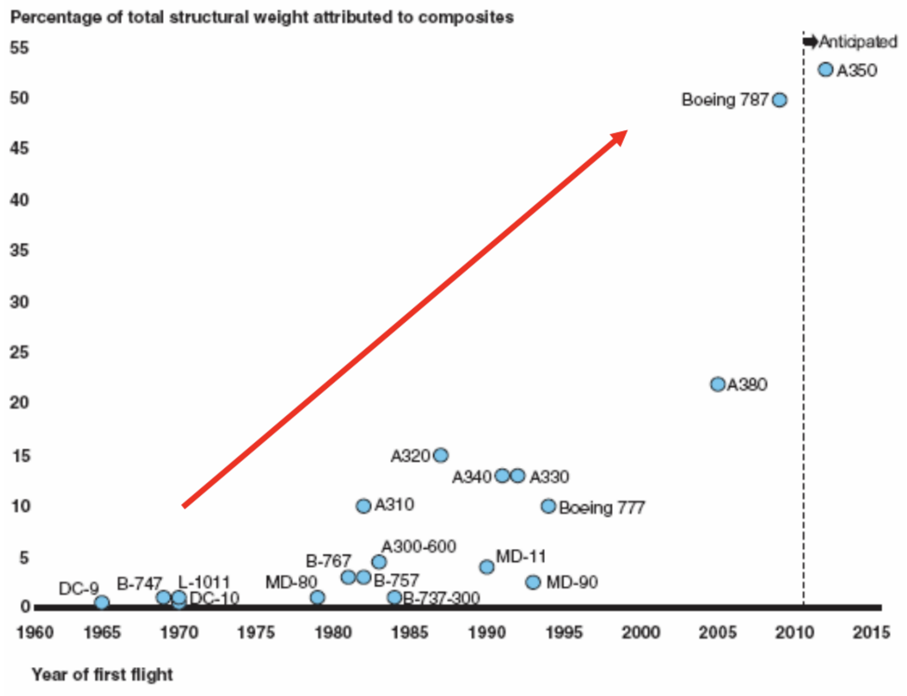


Figure 1: Increase of the presence of composite materials over the years [2]

Globally, there has been a shift in the aerospace sector from metals to composites in recent decades. This increased usage of composites has been driven by the industry need to provide more fuel-efficient aircraft, predominantly through lighter, more efficient products, which also supports legislation and changing attitudes on aviation's impact on the environment. We can summarize the main objective of the aerospace industry in minimize weight keeping the same or more strength than the materials used until now and composites are an ideal candidate.

Improvements in composite design, certification, manufacturing efficiency and through life engineering services, as well as step changes in cost and quality of production systems have been key enablers in realizing these opportunities and have allowed the composites industry to thrive.

Composites materials are critical to aerospace and to the industry's future success in whole aircraft, aerostructures, propulsion and systems markets due their ability to provide high-quality solutions for a range of products. It is essential to understand future requirements and support development of technologies and enabling capabilities in composites.

1.1.2. Definition of composite materials

Aerospace industry is constantly increasing. The passion of aerospace engineers to enhance the performance of its applications is continually contributing to the development and investigation of different high-performance structural materials. [9, 10]

Composites are defined as the combinations of two (or more) distinctively different materials. The resulting products, that is, the composite materials, have better properties than the properties of the constituent materials when considered separately, and are suited for specific applications. A well-designed composite incorporates the best characteristics of each of the component materials.

The components of the composite material must not dissolve or merge completely with each other, that is, materials must be identifiable by physical means, since they are heterogeneous. The fact that composite materials are heterogeneous often means that they are also anisotropic (i.e., they have directionally dependent properties), so their properties will not be the same in all their volume. We can achieve this new compound in different ways:

- **Substantial action** → the appearance of new properties (synergies).
- **Structural action** → the improvement of existing properties.

These composite materials consist mainly of combinations of metals, ceramics, and polymers. There are also composite materials that are naturally occurring materials (such as wood and bone) but we are going to focus on synthetic or man-made composites.

The aim of composite materials is to combine different materials to obtain materials with high stiffness and resistance to fatigue, at low and high temperatures, and obtain also a low density. In brief, it is intended to achieve new materials with a better resistance-weight ratio. This relationship is achieved by using lightweight materials both in the matrix and in the fibers, as long as these comply with the mechanical properties that are desired to be given to the compound.

Composite materials today usually consist in man-made fibers (i.e., a filament that has a large length to diameter ratio), which provide high strength, and some form of matrix which keeps the fibers together, once cured. Also, it allows the stiffness and strength of the material to change with direction of loading.

One of the most favorable points of using composites is that we can reduce the weight maintaining structural and rigidity specifications. Also, composites have more flexible manufacturing processes than other materials, such as aluminum, because their geometries are more complex. The properties of the composite are determined by:

- The properties of the fiber.
- The properties of the resin.
- The ratio of fiber to resin in the composite (fiber volume fraction).
- The geometry and orientation of the fibers in the composite.

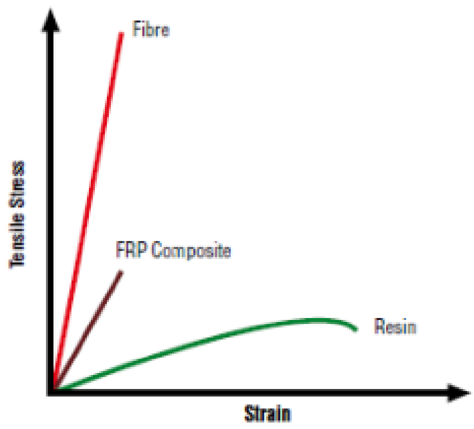


Figure 2: Comparison of the stifness of fiber, composite and resin [3]

The most common thing to observe in aeronautical composites is that such composites break at deformation values much smaller than that corresponding to the yield stress of the matrix, because the matrix is far more ductile than the fiber.

That is, if we assume good adherence between matrix and fibers, the composites usually break when fibers reach their UTS, and this occurs at deformation values much smaller than that of the yield stress of the matrix, because the matrix is far more ductile than the fibers.

The following characteristics are essential to decide if a composite material should be used for the design of any product:

- High specific stiffness and strength per unit weight.
- Low density.
- Electrical insulators.
- Good fatigue resistance.
- Good corrosion behavior.
- Easily moldable to complex shapes.
- Part consolidation leading to lower overall system cost.
- Good fatigue resistance.
- Good corrosion behavior.

If we analyze the compound, we can differentiate two phases:

- The **matrix phase** or resin:

- This phase is continuous and surrounds and covers the reinforcements, the dispersed phase.
- Gives shape to the composite part.
- Keep the phase embedded in its position (binder).
- It gives cohesion to the compound once processed.
- The matrix is the component of the composite exposed directly to the environment. Therefore, it protects the reinforcement from the environment, humidity, chemical attack, and mechanical damage.
- The matrix is the component of the composite that first encounters whatever forces might be imposed, so it transfers the loads onto the dispersed phase.

- The **dispersed phase** or reinforcement:

- This phase is discontinuous and is the resistant element. It is the reinforcement, fiber, tissue, etc.
- Improve matrix properties (strength and stiffness).
- Support the stresses exerted on the compound.
- Mitigate the failures of these characteristics with the increase of temperature.
- Braking or stopping the propagation of cracks through the compound and the development of fissures.
- Dominate other properties such as the coefficient of thermal expansion, conductivity, and thermal transport.

In addition, some properties such as toughness, electrical properties, and damping arise from a strong combination or interaction of the matrix and the reinforcement.

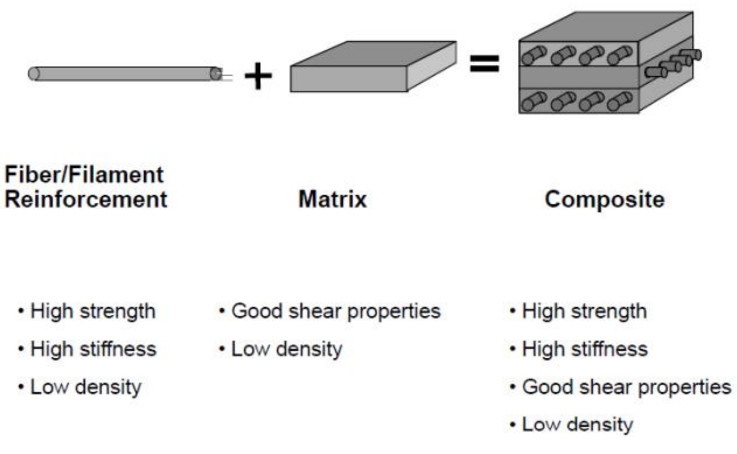


Figure 3: Parts of a compound [3]

1.1.3. Types of composite materials

Composite materials can be classified in two different ways:

- Depending on the **matrix**:

We are going to focus on polymer-matrix composites as the matrix of the samples done in the experimental part of this thesis will be made of epoxy. More information about the other types of composite materials depending on the matrix can be found in **Appendix A**.

- **Polymer-matrix composites (PMC)**

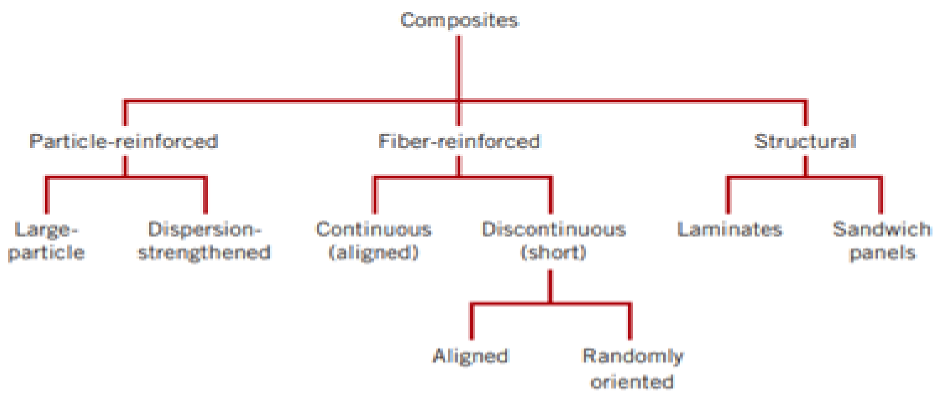
These types of composites are mostly used in commercial civil aviation or in helicopters (i.e. fuselage panels, BIFLEX and TRIFLEX rotor heads, or rotor blades). PMC, thanks to their extraordinary properties, can achieve complex geometries in a single piece. PMC are resistant to corrosion and chemical agents. Moreover, these composites reduce the need of rivets (i.e. a smooth cylindrical shaft with a head on one end), which is a great improvement for aeronautical structures because rivets cause concentration of stresses, which promotes fatigue cracks. In addition, another advantage of PMC is that we can create doublers (i.e. piece of sheet used to strengthen a stiffen an aircraft skin at the location some component is to be attached).

Within this type of composite materials, we can highlight the thermosets and thermoplastics. Thermoset and thermoplastics are two separate forms of polymers, which are differentiated based on their behavior when reacting to the application of heat.

PMC can be divided into two groups, advanced composites and engineering composites. The main difference between both type of composites is the type and length of the fiber reinforcement and in the performance characteristics of the resins used. The advanced composites are formed by long, high-performance reinforcement and resins with superior thermal and mechanical properties. Advanced composites are typically used for aerospace applications like rocket motor cases and airplane parts. On the other hand, engineering composites are characterized by fibers that are both shorter in length and lower in mechanical properties. They are usually made with low-cost thermoset resins or fiberglass or thermoplastic resins with short fibers.

- Depending on the **reinforcement**:

In the next scheme, we show the different types of composite materials according to the **reinforcement**:



<u>Figure 4:</u> Composites according to the reinforcement [4]

We are going to focus on fiber-reinforced composites as the reinforcement of the samples done in the experimental part of this thesis will be made of fibers. More information about the other types of composite materials depending on the reinforcement can be found in **Appendix A**.

- **Fiber-reinforced composites**

In these composites, the dispersed phase is in the form of fibers. Fiber-reinforced composites are the most important composites from a technological point of view.

First, as noted in Fig. 4, fiber-reinforced composites are sub-classified by fiber length. Some critical fiber length is necessary for effective strengthening and stiffening of the composite material. For example, short fibers are too short to produce a significant improvement in strength. The arrangement or orientation of the fibers relative to one another, the fiber concentration and the distribution have an enormously significant influence on the strength and other properties of this type of composites. With respect to orientation, two extremes are possible:

- A parallel alignment of the longitudinal axis of the fibers in a single direction.
- A totally random alignment.

Continuous fibers are normally aligned, whereas discontinuous fibers may be aligned, randomly oriented, or partially oriented. Better overall composite properties are realized when the fiber distribution is uniform. The fibers are longer than the critical length (i.e., minimum length necessary such that the entire load is transmitted from the matrix to the fibers). If they are shorter than this critical length, only some of the load is transmitted.

In discontinuous and aligned fiber composite, the fibers are shorter than the critical length. However, their composite modulus and tensile strengths can approach 50-90% of their continuous and aligned counterparts.

Discontinuous and randomly oriented fiber composites are even less resistant than the previous two because they are positioned randomly. In summary, aligned and continuous fibers gives the most effective strengthening for fiber composites. Discontinuous and aligned fiber composites are less effective in strengthening but they are cheaper, faster and easier to fabricate into complicated shapes. Finally, the only advantage of discontinuous and randomly oriented fiber composites is that the material will be isotropic (i.e., uniformity of properties in all orientations).

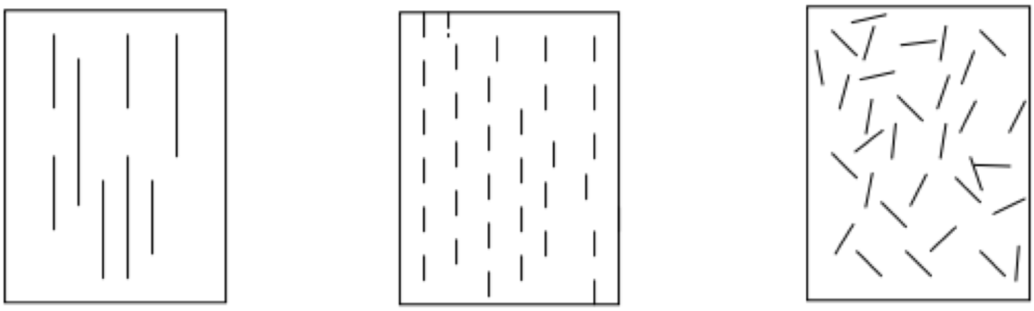


Figure 5: Continuous and aligned fiber composite (left); discontinuous and aligned fiber composite (center); and discontinuous and randomly oriented fiber composite (right) [4]

An important characteristic of most materials, especially brittle ones, is that a small diameter fiber is much stronger than the bulk material. The probability of presence of critical surface flaws and 3D flaws that can lead to fatigue failure diminishes very fast with decreasing specimen size, and this feature is used to the advantage in fiber-reinforced composites. Also, the materials used for reinforcing fibers have high tensile strengths.

On the other hand, the matrix phase of fiber composites may be metal, polymer or ceramic. In general, metals and polymers are used as matrix materials because some ductility is desirable; for ceramic-matrix composites, the reinforcing component is added to improve fracture toughness.

For fiber-reinforced composites, the matrix phase serves several functions:

- It binds the fibers together and acts as the medium by which an externally applied stress is transmitted and distributed to the fibers; only a very small proportion of an applied load is sustained by the matrix phase.
- It should be ductile.

- The elastic modulus of the fiber should be much higher than that of the matrix → $E_m \ll E_f$
- It has to protect the individual fibers from surface damage as a result of mechanical abrasion or chemical reactions with the environment. Such interactions may introduce surface flaws capable of forming cracks, which may lead to failure at low tensile stress levels.
- The matrix separates the fibers and prevents the propagation of brittle cracks from fiber to fiber, which could result in catastrophic failure. Even though some of the individual fibers fail, total composite fracture will not occur until large numbers of adjacent fibers, once having failed, form a cluster of critical size.
- It is essential that adhesive bonding forces between fiber and matrix be high to minimize fiber pull-out. Adequate bonding is essential to maximize the stress transmittance from the weak matrix to the strong fibers.

- **Structural composites**

A structural composite is normally composed of both homogeneous and composite materials, the properties of which depend not only on the properties of the constituent materials but also on the geometrical design of the various structural elements. Structural composites are designed to be light-weight structures maintaining high stiffness and strength. The main requirement of these structures is to stabilize thin surfaces to support tension and compression loads in shear, torsion, and bending.

We are going to focus on laminar composites as the samples done in the experimental part of this thesis will be laminar. More information about the other types of structural composites can be found in **Appendix A**.

- **Laminar composites**

A laminar composite is composed of two-dimensional panels that have a preferred high-strength direction. They have more or less complex geometry with certain orientations that allow them to obtain specific characteristics. The layers are stacked and subsequently cemented together such that the orientation of the high-strength direction varies with each successive layer. The adhesive that is used to join the layers is a polymer hardened by heating and pressure, that is the resin or matrix.

These types of composites have a high resistance in all directions, being also lightweight and cheap. They have interesting thermal properties and are generally designed for their resistance to corrosion. An example is the wood or the continuous and aligned fiber-reinforced plastics.

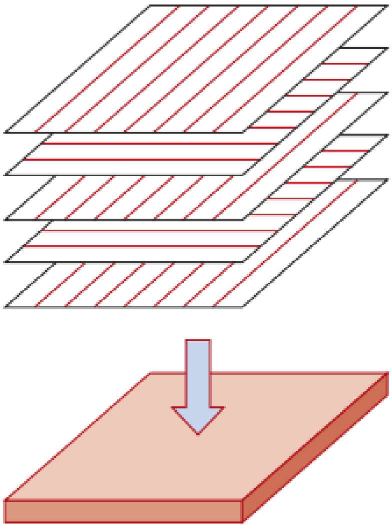


Figure 6: Laminar composite [4]

1.2. Composites materials for aerospace applications

An aircraft's structure must meet the requirements of fuel sealing and provide access for easy maintenance of equipment. Passenger carriage requires safety standards to be followed and these put special demands of fire-retardance and crashworthiness on the materials and design used. For spacecraft, the space environment has to be considered and specially developed materials are required for durability.

It is to be realized that, in order to meet the demands in Table 1, it is necessary to have materials with a specific property-set. The composites and, in particular, the fiber reinforced composites using carbon or aramid fibers in polymer matrices, offer several of these features as given above:

- Light-weight due to high specific strength and stiffness;
- Fatigue-resistance and corrosion resistance;
- Capability for high degree of optimization: tailoring the directional strength and stiffness;
- Capability to mold large complex shapes in small cycle time reducing part count and assembly times;
- Capability to maintain dimensional and alignment stability in space environment;
- Possibility of low dielectric loss in radar transparency;
- Possibility of achieving low radar cross section.

These composite materials also have some weaknesses:

- Laminated structure with weak interferences: poor resistance to out-of-plane tensile loads;
- Susceptibility to impact-damage and strong possibility of internal damage going unnoticed;
- Moisture absorption and consequent degradation of high temperature performance;
- Multiplicity of possible manufacturing defects and variability in material properties.

Even after accepting these weaknesses, the projected benefits are significant and almost all aerospace programs use significant number of composites. The challenges of using composites on such a large scale are many. The composites are not only new but also non-conventional: they are anisotropic, inhomogeneous, have different fabrications and working methods and also different controls for quality assurance. They have a complex material behavior under load requiring new and complicated analysis tools. Moreover, the behavior is not always predictable by analysis and this makes reliance on several expensive and time-consuming tests unavoidable.

The materials systems which have been considered useful in aerospace sector are based on reinforcing fibers and matrix resins. The reinforcing fibers commonly used in aerospace applications are the following:

- **Glass-fiber reinforced polymer or epoxy (GFRP, GFRE)**

Because of their extremely good mechanical properties GFRE is the reinforcement par excellence. It is a fiber reinforced polymer made of plastic matrix reinforced by fine fibers of glass.

Regarding the Ultimate Tensile Strength (UTS) of fibers, UTS has disparate and very low values comparing to the theoretical limit, this happens because of the break of bounds due to the presence of defects.

Fibers are used because they have UTS higher than the same material in ingot format. When the volume of the material increase, the probability of enormous defects also increases. This phenomenon is shown by the Griffith experiment.
GFRE is lightweight, extremely strong and robust, it has low density and it is a good insulator. In fact, GFRE has the highest UTS. Otherwise, it has some lower properties than CFRE as it is less stiff, and the material is typically far less brittle. It has insufficient strength for primary structure.

- **Carbon fiber reinforced polymer or epoxy (CFRP, CFRE)**

This fiber is an extremely strong and light fiber-reinforced polymer which contains carbon fibers. The composite may contain other fibers, such as aramid, aluminum or glass fibers, as well as carbon fibers.

As we can observe in Table 1, we can affirm that carbon fibers have the highest tensile strength and stiffness (E-Modulus), the lowest strain and the highest temperature range. In addition, carbon fibers have a high degree of vibration attenuation.

We can summarize all this information in the following table:

Fibre	Density (g/cc)	Modulus (GPa)	Strength (GPa)	Application areas
Glass				
E-glass	2·55	65–75	2·2–2·6	Small passenger a/c parts, aircraft interiors, secondary parts; Radomes; rocket motor casings
S-glass	2·47	85–95	4·4–4·8	Highly loaded parts in small passenger a/c
Aramid				
Low modulus	1·44	80–85	2·7–2·8	Fairings; non-load bearing parts
Intermediate modulus	1·44	120–128	2·7–2·8	Radomes, some structural parts; rocket motor casings
High modulus	1·48	160–170	2·3–2·4	Highly loaded parts
Carbon				
Standard modulus (high strength)	1·77–1·80	220–240	3·0–3·5	Widely used for almost all types of parts in a/c, satellites, antenna dishes, missiles, etc
Intermediate modulus	1·77–1·81	270–300	5·4–5·7	Primary structural parts in high performance fighters
High modulus	1·77–1·80	390–450	2·8–3·0 4·0–4·5	Space structures, control surfaces in a/c
Ultra-high strength	1·80–1·82	290–310	7·0–7·5	Primary structural parts in high performance fighters, spacecraft

Table 1: Fibers used in aerospace industry [5]

The most commonly used thermosetting resins as matrices in aerospace industry are showed in the following table:

Thermosets				Thermoplastics
Forms cross-linked networks in polymerization curing by heating				No chemical change
Epoxies	Phenolics	Polyester	Polyimides	PPS, PEEK
• Most popular • 80% of total composite usage • Moderately high temp. • Comparatively expensive	• Cheaper • Lower viscosity • Easy to use • High temp usage • Difficult to get good quality composites	• Cheap • Easy to use • Popular for general applications at room temp	• High temp application 300°C • Difficult to process • Brittle	• Good damage tolerance • Difficult to process as high temp 300–400°C is required
• Low shrinkage (2–3%); • No release of volatile during curing	• More shrinkage • Release of volatile during curing	• High shrinkage (7–8%)		
• Can be polymerized in several ways giving varieties of structures, morphology and wide range of properties	• Inherent stability for thermal oxidation. • Good fire and flame retardance • Brittle than epoxies	• Good chemical resistance • Wide range of properties but lower than epoxies. • Brittle • Low T_g		
• Good storage stability to make prepregs	• Less storage stability-difficult to prepreg	• Difficult to prepreg		• Infinite storage life. But difficult to prepreg
• Absolute moisture (5–6%) causing swelling and degradation of high temp properties • Also ultra violet degradation in long term	• Absorbs moisture but no significant effect of moisture in working service range	• Less sensitive to moisture than epoxies		• No moisture absorption
• Density (g/cm^3) 1·1–1·4	• Density (g/cm^3) 1·2–1·4	• Density (g/cm^3) 1·1–1·4		• Density (g/cm^3) 1·3–1·4
• Tensile modulus 2·7–5·5 GPa	• Tensile modulus 2·7–4·1 GPa	• Tensile modulus 1·3–4·1 GPa		• Tensile modulus 3·5–4·4 GPa
• Tensile strength 40–85 MPa	• Tensile strength 35–60 MPa	• Tensile strength 40–85 MPa		• Tensile strength 100 MPa

Table 2: Matrices used in aerospace industry [5]

We are going to focus on epoxy resin as the samples done in the experimental part of this thesis will be made of epoxy. More information about the other types of resins used in the aerospace industry can be found **Appendix A**.

Epoxy resins are the most used resins in high quality composite materials because they have better physical and mechanical properties than vinylester and polyester and have a moderate cost.

Epoxy resin has a good adhesion capacity so we can obtain laminates with a high content of fiber. The strength and stiffness are superior for epoxies. The creep resistance is also superior for epoxies, so they can operate at higher temperatures. Most epoxy resins need the contribution of external heat to cure them, through a curing or post-curing process.

In contrast to polyester thermosets, about 50% of all epoxy resins are used for nonreinforced applications. This resin is the strongest one (3 times compared to other resins), but it is expensive. Also, we can perform virtual leak test and it adheres to older epoxy.

The concern in using composites arises mainly due to the high demands of reliability and safety of aerospace structures, given the complexity of composite behavior and consequent difficulties in building prediction models. This creates an excessive reliance on testing at all stages: design and development, proving and certification, and in-service inspection and repairs. The cost of such testing is sometimes enormous, and this has led to some skepticism in the future use of composites.

1.3. Advantages and disadvantages of composites

Some of the most important advantages and disadvantages of composites are listed in the following table:

ADVANTAGES

- Lightweight
- High specific stiffness
- High specific strength
- High impact resistance
- High dielectric resistance
- Tailored properties (anisotropic)
- Easily moldable to complex shapes
- Thanks to its easy handling, there is less waste of material
- Part consolidation leading to lower overall system cost
- Easily bondable
- Good fatigue resistance
- Good damping
- Good corrosion behavior
- Crash worthiness
- High damage tolerance → Improvement of accident survivability
- Internal energy storage and release
- Low thermal expansion
- Low electrical conductivity
- Stealth (low radar visibility)
- Thermal transport (carbon fiber only)

DISADVANTAGES

- Lack of well-proven design rules as it is a relatively new material
- Metal and composite designs are seldom directly interchangeable
- Long development time
- Manufacturing difficulties (manual, slow, environmentally problematic, poor reliability)
- Initial cost of raw materials is higher than the cost of the raw material of the conventional materials
- Fasteners
- Low ductility (joints inefficient, stress risers more critical than in metals)
- Solvent/moisture attack
- Temperature limits
- Damage susceptibility
- Hidden damage → Non-visible impact damage
- Maintenance of raw material must be carried out in specific environmental conditions → Cost increase in final product
- Manufacturing process is not very automated → Greater involvement during process by workers
- The handling of composite materials must be careful, since the dust they issue when they are cut, if inhaled it can be dangerous for workers → It is required to work with the safety equipment

1.4. Calculation of elastic modulus using different approaches

The Young's modulus or elastic modulus (E) is associated with the strength of the interatomic bonds and it is the macroscopic average of testing a mesh of bond in all directions. If most of these bonds are oriented in the external strength direction, then the elastic modulus grows. For example, if we have a monocrystal, depending on we apply the strength we can obtain different values of E because of the orientation of the bounds in the strength direction. There are two different ways to calculate E:

1. By **experimental data**.

Obtaining the Young's modulus from experimental data is possible when you have a graphic with the required data. A plot obtained from the experimental part of this thesis will be used to show how to calculate the Young's modulus from experimental data. This is an example of a composite sample of GRFP with 12 layers.

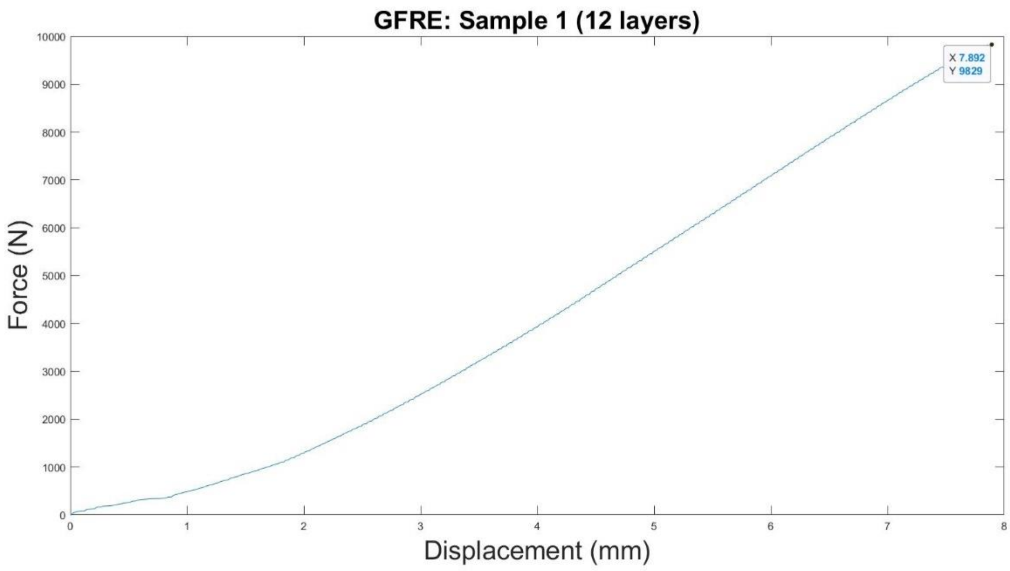


Figure 7: Force-Displacement plot of a sample of GFRE

As we obtained a Force-Displacement curve, it can be calculated directly from the data the maximum force that the composite will be able to support until it breaks, together with the maximum strain or deformation that the compound will experience. That is:

- Force and strain:

The force and the strain are located at the end of the line of the plot, as this point represents the exact moment when the composite breaks.

Force (N)	Displacement (mm)
9.829,00	7,892

Table 3: Force and displacement corresponding to the maximum point of the Fig. 7.

Then, using some formulas it is possible to calculate most important mechanical properties of the composite:

- Stress (MPa):

$$\boldsymbol{\sigma = \frac{F}{A}} \qquad \textbf{(1.1)}$$

σ = stress supported by the composite
F = force applied to the composite
A = area where the force is applied

- Young's modulus (GPa):

$$\boldsymbol{E = \frac{\sigma}{\varepsilon}} \tag{1.2}$$

E = Young's modulus
σ = stress supported by the composite
ε = strain experienced by the composite

- Elongation (mm):

$$\boldsymbol{\Delta L = \varepsilon \cdot L_0} \tag{1.3}$$

ΔL = total elongation
ε = strain experienced by the composite
L_0 = initial elongation

2. By **rule of mixtures**.

The rule of mixtures approach is a useful method in determining the engineering and physical properties of plies in a laminate. It is based on the knowledge of the properties and fraction volume of fibers and resin (generally provided by the manufacturer). By mixing them in different volume fractions, we can obtain different values of the E. The principal term used in the rule of mixtures approach is the **fiber-volume fraction** or fiber-volume ratio (V_f). The total expression is: [6]

$$\boldsymbol{V_f + V_m + V_v = 1} \tag{1.4}$$

V_f = fiber-volume ratio, which is the physical volume of fibers to the total ply volume
V_m = matrix or resin-volume ratio
V_v = void volume ratio, which is the volume of voids and porosity as a result of the process used

The following equations result in the engineering and physical properties that can be determined using the rule of mixtures approach. In using these equations, please note the following:

1. The void content is assumed to be zero.
2. Voids reduce the fiber-volume ratio.
3. Voids are a result of the manufacturing method and the cure process used.

In some cases, the fiber or resin property cannot be easily determined. However, by measuring the ply property and determining the fiber- and resin-volume ratios, the individual fiber or resin properties can be estimated. The following equations determine different properties of composites materials.

- Density:

$$\boldsymbol{\rho = V_f \rho_f + V_m \rho_m} \tag{1.5}$$

ρ = total density
ρ_f = density of fibers
ρ_m = density of matrix

- Longitudinal stiffness (Young modulus):

$$\boldsymbol{E = V_f E_f + V_m E_m} \tag{1.6}$$

E = Young's modulus of a ply or single layer (laminate)
E_f = Young's modulus for fibers
E_m = Young's modulus for matrix

- Poisson's ratio:

$$\boldsymbol{\upsilon = V_f \upsilon_f + V_m \upsilon_m} \tag{1.7}$$

υ = major Poisson's ratio of a ply or single layer (laminate)
υ_f = Poisson's ratio for fibers, which is difficult to measure
υ_m = Poisson's ratio for matrix

- Shear modulus:

$$\boldsymbol{G = \frac{1}{\left[\frac{V_f}{G_f} + \frac{V_m}{G_m}\right]}} \tag{1.8}$$

G = shear modulus of a ply or single layer (laminate)
G_f = shear modulus of fibers
G_m = shear modulus of matrix

- Tensile strength (longitudinal):

$$\boldsymbol{\sigma = V_f \sigma_f + V_m \sigma_m} \tag{1.9}$$

σ = axial stress strength of a ply o singles layer (laminate)
σ_f = axial strength of fibers
σ_m = shear strength of matrix

Generally, there is a difficulty in determining the measured value of fiber-volume ratio in a fabrication process. Occasionally the weight ratios of the fiber a resin are used, but weight ratios cannot be used directly to determine the engineering properties. To determine the fiber- volume ratio from weight ratios, the fiber, resin, and ply densities must be known. The densities can be found in the manufacturing safety data sheet (MSDS) or materials data sheet (MDS) documentation. If the individual fiber and resin densities are not known, but the ply density and fiber-volume ratio are provided, then use Eq. 1.10.

The expression that determines the fiber-volume ratio from the fiber and resin weight ratios is:

$$\boldsymbol{V_f = \left[1 + \frac{1}{\left(\frac{W_f}{W_r}\right) + \left(\frac{\rho_r}{\rho_f}\right)}\right]^{-1}} \tag{1.10}$$

W_f = weight of the fiber
W_r = weight of the resin system
ρ_r = density of the resin system
ρ_f = density of the fiber

1.5. Composite stacking sequence rules

The main stacking rules regarding composite design are as follows: [2]

1. **Symmetry**

A laminate is symmetric when the plies above the mid-plane are a mirror image of those below the mid-plane. The plies need to be symmetrically laid around neutral axis. If it is not possible, the asymmetry needs to be as close as possible to the neutral axis. The main objective of this rule it to avoid deformation during the manufacturing process.

2. Balance

A laminate is balanced when it has equal numbers of negative and positive angled plies, it means that for each ply in the positive direction there is a ply in the negative one. The main objective of this rule is to avoid internal stresses and deformation during the manufacturing process, and it is mandatory.

3. Plies orientation percentages

The main objective of this rule is to make sure that design intent is maintained during the manufacturing process:

- The minimum percentage of plies per orientation equals to 8%.
- The maximum percentage of plies per orientation equals to 67%.

4. External plies

The main objective of this rule is to ensure minimum requirement for component's impact resistance:

- At least 2 full plies required to be on the surface.
- External plies must not be oriented in the main load direction.

5. Maximum grouping

The main objective of this rule is to reduce micro-crack formation. The grouping of consecutive layers with similar orientation should be minimized. It is recommended not to stack more than four consecutive plies with the same orientation. The maximum number of plies depends on the ply thickness using the following formula:

$$n_{max} = 4\,plies$$

$$\mathrm{t_{max}} = 0.8 \text{ or } 1 \text{ mm}$$

For example:

- If the ply thickness is **0.125 mm**, the maximum is **4 plies** (total thickness is 0.5 mm).
- If the ply thickness is more than **0.25 mm**, the maximum is **3 plies** (total thickness lower than 1 mm).

6. Interlaminar shear

The main objective of this rule is to minimize inter-laminar shear effect. The angle between two adjacent plies should be minimized. It is important to avoid 90º change orientations.

The preferable way is the following:

45
0
135
90
45
0

There are no two consecutive plies with a change of 90º of orientation.

The least preferable way is the following:

0
90
45
135
45
0

There are two consecutive plies with a change of 90º of orientation → 0º-90º / 45º-135º

7. Damage tolerance

The main objective of this rule is to optimize damage tolerance and bolted repairs. The outer plies of the laminate should not be at the direction of the main load and should be at 45º or 135º (or a combination of 45º and 135º). This is because 45º or 135º are the best possible case.

8. Coupling effect

The main objective of this rule is to minimize coupling effect. It means that it is preferable that the 45º plies should be grouped in pairs with the 135º plies.

1.6. Types of manufacturing techniques: advantages and disadvantages

First, it must be said that there are different criteria to select the suitable manufacturing method: [6]

- Criteria 1: **technical / technological specifications**

  - Fiber and pores volume.
  - Dimensions, geometry and dimensions tolerance.
  - Surface finish.

- Possibility of inserts in piece.
- Outgassing.

- Criteria 2: **productive parameters → cost per piece**

  - Start-up and production times.
  - Needs and cost of equipment, labor, tools, materials…
  - Production rate.
  - Level of automation.
  - Size of the series to be produced.

When we have decided which criteria is the best for a concrete case, we must choose the convenient manufacturing technique.

Contact is the simplest technique to mold a composite. It puts fibers into an open mold and then adds resin to the fibers. After ensuring that the fibers are fully wetted by the resin, the resin is cured.

We can differentiate the contact techniques according to the starting material or according to the required specifications and the way of placing fibers into the mold if structural requirements are not very demanding.

The methods of placing the fibers into the mold can be divided into two general methods: lay-up or spray-up.

In these techniques the hand of the operators plays a very important role, since it depends on him the resulting laminate. The mold can be made of many materials, but we assumed a single-sided mold (that is, open) and not covered by a second rigid mold part during cure, although it might be covered by a flexible sheet.

We are going to focus on hand lay-up technique as it is the one used to perform the experimental part of this thesis.

In lay-up, the fibers are in the form of broad goods, usually fabric or mat. It is assumed that the fibers are placed into the molt in a manual process.

Hand lay-up is the simplest composites open molding method. As mentioned before, this process is carried out in an open mold, properly conditioned. The resin is mixed with an initiator (catalyst) or hardener in a mixing bowl, otherwise, curing can take days or weeks. Then, it is stirred to ensure full dispersion. When fully mixed, the proper amount of resin is transported to the mold. The reinforcements are placed in the mold and we apply the resin by rolling it into the reinforcements. When the fibers are wetted, a change in color is noted as the resin is absorbed.

There are no limits regarding the size or the shape of the piece to be produced. It is possible to create large and complex products. In fact, the largely manual nature of lay-up molding makes it the method of choice for some parts that, usually because of high complexity shape, can only be made by this method. The wide variety of parts that can be made leads to a wide variety of curing conditions and materials. A wide variety of resins can be used and consequently, many catalysts or hardeners can be chosen for use with them. If only a few parts of any design are to be made, lay-up is usually the most effective method of manufacture because it is no need to use complex processing methods and tooling. Hand lay-up is ideal for short production and it is not necessary a high economic investment.

On the other hand, this process has also disadvantages. Depending on the piece, the workforce can be numerous, and the composite quality depends enormously on the ability and motivation of the laminators. Another disadvantage is that usually the composite is ended up with an excess of resin which compromises the mechanical properties of the composites. Too much resin leads to a worsening in the strength of the laminate. It is very difficult to achieve the perfect weight-ratio of resin to fabric, in this case, the fibers.

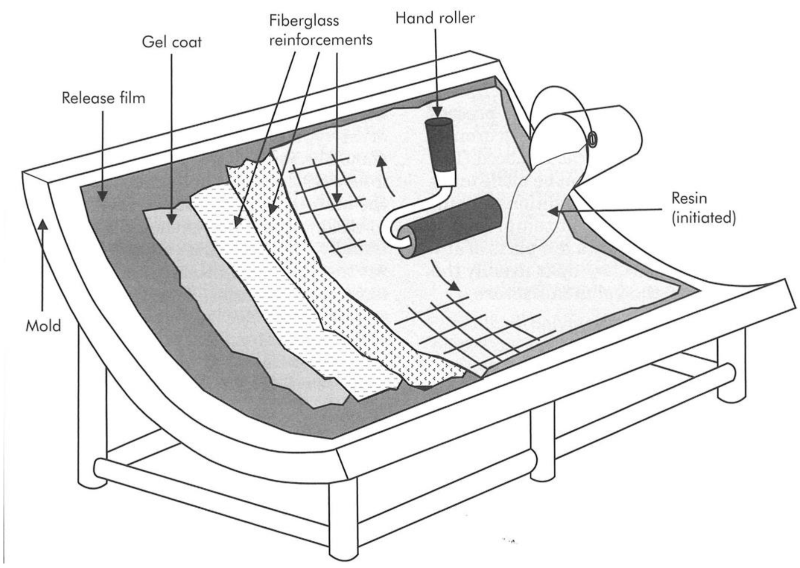


Figure 8: Hand lay-up process [6]

Finally, it is important to state that when manufacturing composites with this technique, the lay-up process, it is inevitable that the air strays trapped between the layers. If some of the air is removed after the lay-up and before the part is cured, it is possible to obtain a resulting part with better mechanical properties. After that, during the curing process, it is also important to remove the air between the lays, as the resin is heated and consequently, the part moves easily. This process of air evacuation is called debulking.

The debulking is applied after the part is cured when the number of plies is up to four. When the number of plies is large, from four plies, it is required to apply one or more debulking operations. This usually occurs after each lay-up of four to six plies.

With this debulking process it is possible the elimination of volatiles. Therefore, the resulting part has a lower void content. Another advantage occurs when some resin may move out of the layers and it is absorbed by materials placed in the bagging system. This absorption causes a moderate loss of resin that increases the fiber/resin ratio and reduces the total weight without significantly reducing the mechanical properties of the composite.

There are also some disadvantages as the vacuum should be carefully monitored during the debulking process to ensure that there are no leaks. Another inconvenient is the impossibility of detecting the break of the bag as it is not detected until the part is cured and, consequently, it is too late to remedy.

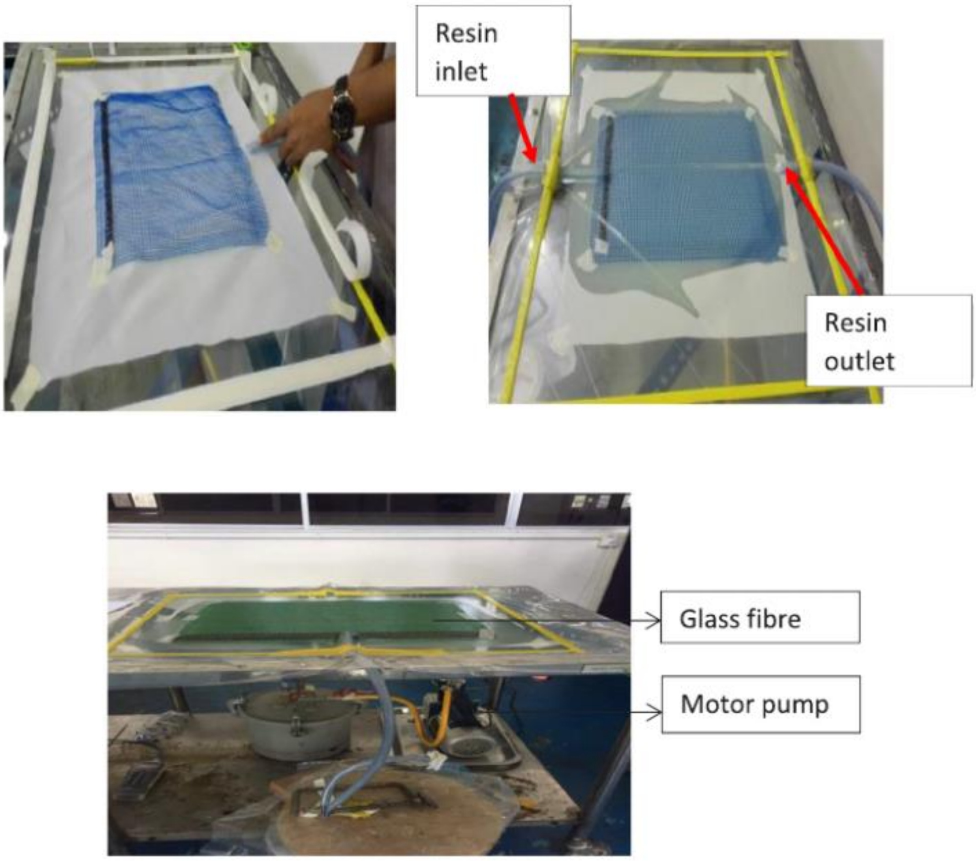


Figure 9: Vacuum bagging process [7]

CHAPTER 2. METHODOLOGY

2.1. Experimental methodology

This chapter describes the experimental part of this thesis. As mentioned in the introduction, we will manufacture different specimens to determine which one has the best mechanical properties using the UTM, depending on the number of layers of each sample, and the materials used. We will use carbon fibers and glass fibers to manufacture the desired composites samples. In order to carry out the experiments correctly, we must follow a well-defined path that it is explained below.

2.1.1. Planning

Design specification is one of the most important steps in the design and manufacturing of a composite. Once it was decided we would only make samples with GFRE because we already had the necessary experimental data for CFRE samples thanks research in the literature [8]. We must determine how much samples we want to do, the layers of each sample, the disposition of the fibers, and their orientation and the specific material needed to be able to make the required samples. First, we decided to make 8 samples of GFRE. Second, according to the number of layers and the orientation of the fibers of each sample, we will proceed as follows: 4 samples of CFRP with 6 and 12 layers with the following orientations (in degrees), fulfilling the golden rules previously mentioned:

45/135
0/90
0/90
0/90
0/90
45/135

45/135
0/90
0/90
0/90
0/90
45/135
45/135
0/90
0/90
0/90
0/90
45/135

Figure 10: Orientations of 6 layers and 12 layers samples, respectively

Once we have decided these parameters of our samples, we have purchased the following material:

- GFRE with an orientation of 0º/90º.
- 3 kg of epoxy.
- 3 stirrers.
- 3 mixing bowls.
- 3 brushes.

In order to give continuity to this project and to quantify the amount of money required to do these experiments, it is essential to provide the budget of all the material specified above: **73,57€**. All these products have been bought to *SagristàProducts* based on Barcelona.

Finally, we state that the volume fraction of fiber and epoxy are both about 50%, as we assumed full cohesion between the fibers and the resin.

2.1.2. Dimensions

The second step is to determine the dimensions of the samples. The GFRE samples of 6 layers have a thickness of 1,2 mm and the samples of 12 layers have a thickness of 2,50 mm, approximately:

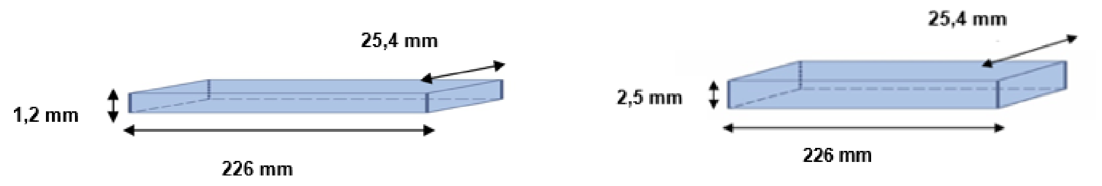


Figure 11: Dimensions of the 6 layers sample and 12 layers samples of GFRE, respectively

Otherwise, the CFRE samples of 6 layers have a thickness of 1,45 mm and the samples of 12 layers have a thickness of 2,70 mm. [8]

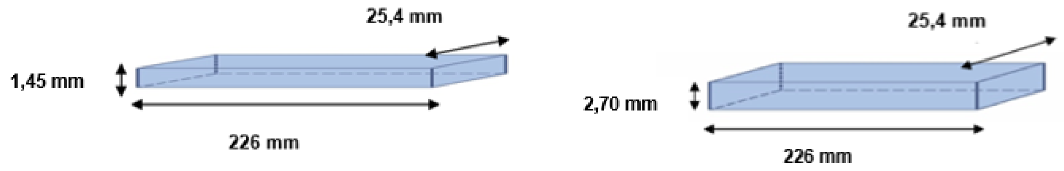


Figure 12: Dimensions of the 6 layers sample and 12 layers samples of CFRE, respectively

2.1.3. Fabrication

After specifying all the characteristics of the samples, we should start the fabrication process. Considering the university resources, we will use the hand lay-up method because it is the simplest one, as explained in the manufacturing techniques chapter. The fabrication process is divided in two main groups: one for the GFRE and one for the CFRE. Both processes are very similar, but they are slightly different in the way the fibers are handled.

2.1.3.1. Samples of GFRE

STEP 1 With the help of a marker, we have to draw as many rectangles in the GFRE as layers we want in the final composite. If we want to do a composite of six layers, we have to draw six rectangles (see Fig. 13).

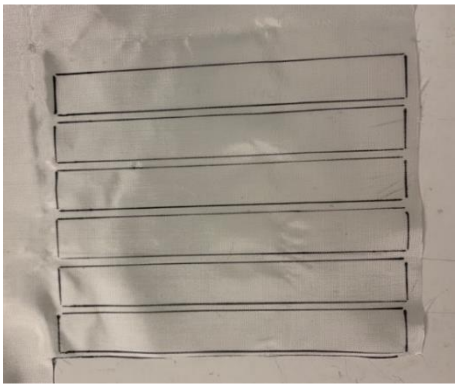


Figure 13: Rectangles of GFRE drawn and cut, respectively

STEP 2 Once the rectangles are drawn, we have to cut these rectangles carefully (see Fig. 13). We have to be very careful because the fibers move very easily.

STEP 3 The next step is to check which part of the bowl we must use regarding the legend of the hardener bottle. As we can see in Fig. 14, in our case is 2:1 by volume or 100:47 by weight. We have to highlight the importance of this step because depending on the hardener that we bought these ratios can change.

Figure 14: Hardener bottle

STEP 4 Now, we have to fill the mixing bowl with epoxy up to letter A of the corresponding part (see Fig. 15). As we mentioned before, in our case it is 2:1.

STEP 5 Then, we pour in hardener until letter B, and mix these two components with the help of a stirrer (see Fig. 15) until we feel comfortable with the mixture.

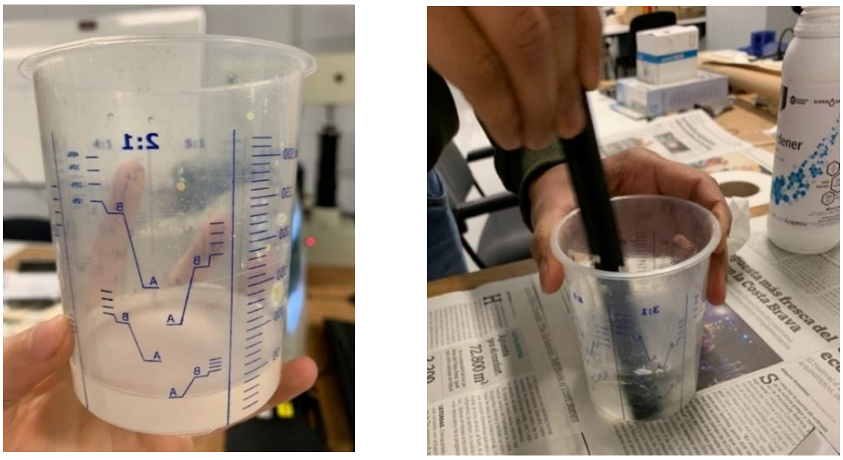


Figure 15: Mixing bowl and final mixture, respectively

STEP 8 After that, we apply an epoxy layer above the surface on which we will do the experiment, giving a better finish to the part. Then, we apply the first rectangle of glass fiber. Using the mixture obtained before we have to make brushstrokes above the glass fiber until it absorbs all the mixture done before (see Fig. 16).

Figure 16: Procedure of how to do the plies of the composite

STEP 9 Finally, we repeat the same process with the other five rectangles of fiber until we obtain the final composite sample (see Fig. 17).

Figure 17: Final GFRE samples

Once arrived at the end of the fabrication part of the experiments it is essential to state how much time takes to do the samples. In total, it is needed approximately **2:25 h**.

# layers	# samples	Time (min)	Total (min)
6	5	9	**45**
12	5	18	**90**

Table 4: Time required to manufacture the samples

2.1.3.2. Samples of CFRE

In this case, we will use samples of carbon fiber already done by a UPD professor [8]. But we will show how to do the realization of the composite because it is a bit different than the GFRE.

To do a composite with carbon fibers we have to follow the same steps that we followed to do the GFRE samples but being very carefully in **STEP 1** and **STEP 2**.

It is important to note that CFRE is much more flexible and elastic and moves much more easily than GFRE. CFRE is very difficult to handle because if we cut directly on the big layer, all fibers would stop being together and the whole fiber layer would break down. Therefore, we have to be very carefully in the first steps.

STEP 1 The most important difference between GFRE and CFRE is that we can cut directly on the GFRE, but we cannot cut directly on the CFRE. With the help of a scotch tape, we will get the fibers to stop moving so easily and it would be easily the cut of the fibers (see Fig. 18). Then, we have to draw the rectangle on the big layer of carbon fiber.

STEP 2 After that, we have to cut the rectangles using the scotch tape as reference. We have to cut through the middle of the scotch tape so that the fiber does not break down (see Fig. 18). Then, we have to remove the scotch tape very carefully so that the fibers do not fray.

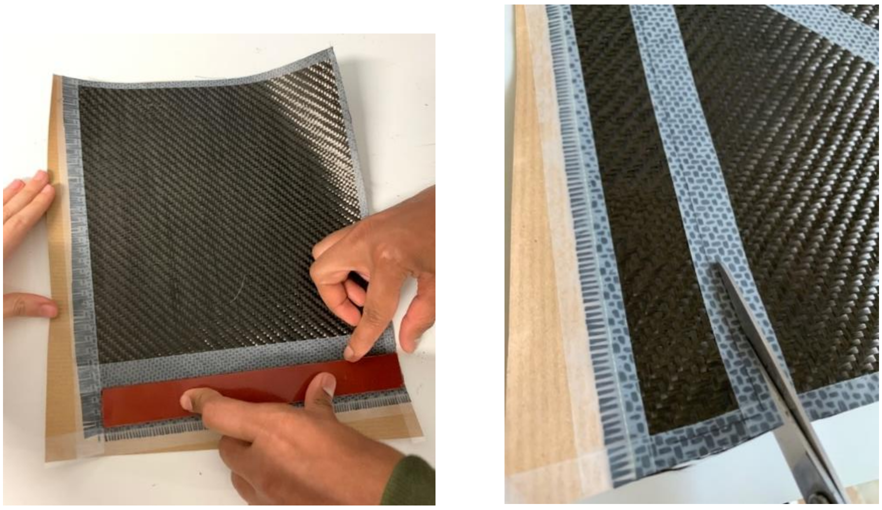


Figure 18: Procedure of how to draw and cut the rectangles of CFRE

Finally, all the following steps are the same as in the GFRE. We just need to follow step by step all the indications and we will obtain the CFRE resulting parts very easily. As the whole process to manufacture CFRE samples is very similar to the manufacturing process of GFRE, it is guessed that the time required to finish the samples would be approximately **2:45h**. The time would be a little bit higher because CFRE moves much more easily, and it would take more time to cut the rectangles.

2.1.4. Curing

Once the samples have been made, it is essential to apply a sufficiently long curing time for the samples to achieve their best mechanical properties. Curing is a chemical process employed in polymer chemistry and process engineering that produces the toughening or hardening of a polymer material by cross-linking of polymer chains. Most epoxies are cured at elevated temperatures to facilitate the movement of the resins and hardeners. Some heating may be required just to make the epoxy and the hardener liquid at room temperature (RT).

The temperature selected for curing the epoxy depends strongly on the nature of the resin and hardener. Some resins and, especially, some hardeners do not react readily at RT and needed higher temperature to reduce the curing time to a reasonable level. The performance of the polymer is often related to the cure temperature. A general rule is that the maximum temperature at which the resin will be used, should not exceed the glass transition of the polymer, which usually increases with increasing the cure temperature. Therefore, epoxy used at high temperatures need to be cured at even higher temperatures.

In our case, we do not have the machinery or the necessary tools to carry out the curing process at high temperatures, so our samples will be cured at RT. This curing is initiated merely by the mixing of the epoxy and the hardener. Composites that cure at RT are normally used for the following applications: household adhesives, electrical potting, and simple coatings. In addition, for curing resins at RT, it can be considered that they cure fully in general in one week. So, we must wait for **one week** to do the following step: the tests of our samples with a UTM.

2.1.5. Testing

Finally, in order to analyze the fabricated samples, we will use the Metrotest's UTM located in the laboratory of EETAC-UPC, controlled by a personal computer with Metrotest software. A UTM is used to test both the tensile and compressive strength of materials. Universal Testing Machines are named as such because they are versatile and valuable pieces of testing equipment that can perform many different tests on an equally diverse range of materials, components, and structures. Most UTM are modular and can be adapted to fit the customer's needs. Particularly, the UTM allows evaluating mechanical properties such as the elastic modulus, yield strength, ultimate strength, elastic and plastic deformation, and strain hardening, under different loading modes such as tension, flexion, and compression. Different UTM have different load capacities, some as low as 5 kN and others as high as 2,000 kN. Tests can also be performed in controlled environmental conditions when the UTM is placed into an environmental room or chamber.

To use this machine, we must follow the next steps:

- First, we put our sample between the clamps (see Fig. 20) of the machine and we make sure that the sample is as stressed as possible.
- Then, using the computer and the corresponding program we started the test.
- Finally, we will know the test is finished when the sample breaks in two pieces.

Fig. 19 shows the LCD screen of the UTM that gives us information about all the experimental process: F is the force that the sample supports in each moment during all the process, E is the elongation that the specimens experiment during all time, and V is the velocity that we have stablished before when configuring the data of the computing program.

Through this screen and/or the ad hoc software for UTM data acquisition, processing and display, we can monitor our experiment. For example, we know that the strength should increase jointly with the elongation. If we notice that one of these values increases and the other decreases, we know that something is going wrong, so we must revise the input parameters.

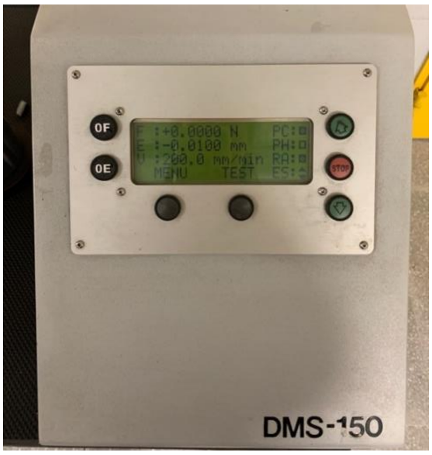


Figure 19: LCD screen of UTM

Through the UTM tests, we will measure the force (N), the displacement (mm) and the time (s).

The tensile tests were performed at a displacement rate of 6 mm/min. The crosshead displacement and load from the load cell were recorded during the test at a sampling rate of 10 readings per second. From these measurements, we can obtain different mechanical properties of each sample and material to evaluate the behavior of GFRE and CFRE.

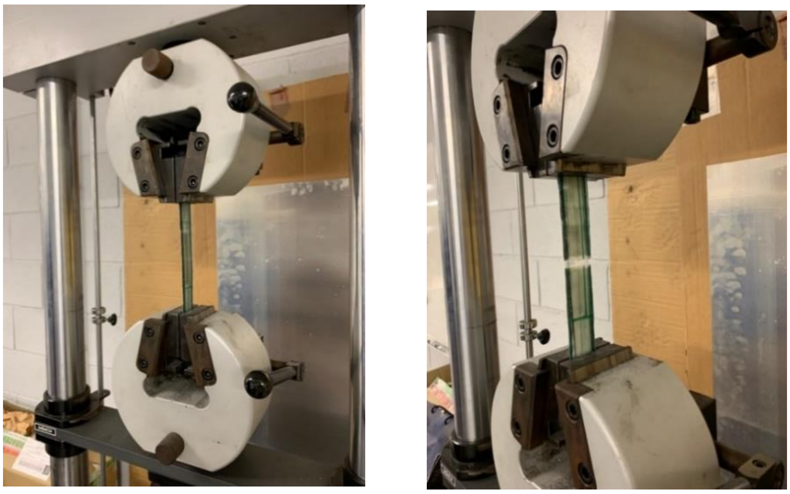


Figure 20: GFRE sample before and after a UTM test, respectively

As in the previous sections, it is fundamental to state how much time takes to do all the tests. In total, it is needed approximately **17,5 min**.

# layers	# samples	Time (min)	Total (min)
6	5	1,5	**7,5**
12	5	2	**10**

Table 5: Time required to manufacture the samples

2.2. Numerical analysis methodology

This part consists on analyze the behavior of the samples made in the experimental part of this thesis through an appropriate software as it is *Abaqus CAE*. From the data obtained in the previous section, the different average for the different type of composites will be used to be able to obtain the corresponding images of the stress distribution. We will simulate CFRE samples and GFRE samples with 6 layers and 12 layers, obtaining 4 different figures of the stress distribution.

In addition, we will give some input parameters to the software to calculate the corresponding ultimate force of each sample. Then, the obtained force will be compared with the ultimate force calculated from the experimental part.

To obtain the desired results different conditions must be imposed in the software and then, we have to let the software simulate each scenario. The parameters to be established are the following:

- The dimensions of the samples. See Fig.11 and Fig. 12.
- The properties of the samples → Young's modulus and orientations of the layers. See Fig. 10 and Table 12 and Table 18, respectively.
- The load applied to the sample, that is, the displacement. See Table 7 and Table 14.

CHAPTER 3. EXPERIMENTAL AND MODEL RESULTS

This part of the thesis includes the processing of the experimental and model results of the GFRE and CFRE samples done in the laboratory.

3.1. Experimental results

Through an appropriate equipment as it is the UTM, some relevant values have been obtained in order to analyze the behavior of the samples with different characteristics.

It is important to state that fiber strength decreases greatly in the presence of surface defects. The surface of fibers can be treated with a sizing, finish, or coupling agent to improve mechanical properties. In this case, considering the available resources and the manufacturing process used (hand lay-up), the fiber strength is not as good as it should be in different conditions.

3.1.1. GFRE composites

After performing the tests, we have obtained the following results:

3.1.1.1. Ultimate force (N)

As explained before, from the data provided by the tests with the UTM, we will obtain directly the force, the displacement and the time. Time is not very important, since we will not use it for any calculation, but it gives us information about the resistance of the material. For given test conditions, the sample that lasts longer under traction is the one that is most resistant.

Layers	**Sample 1**	**Sample 2**	**Sample 3**	**Average**	**Std. dev.**
12	9.829,40	7.865,54	10.207,07	**9.300,67**	**1.026,44**
Layers	**Sample 4**	**Sample 5**	**Sample 6**	**Average**	**Std. dev.**
6	5.458,54	4.501,79	5.010,38	**4.990,24**	**390,85**

Table 6: Ultimate force (N) of GFRE samples

3.1.1.2. Final elongation (mm)

The final elongation is also obtained from the data provided by the UTM tests. It is the total increment in length in millimeters that the sample experiences during the test.

Layers	Sample 1	Sample 2	Sample 3	Average	Std. dev.
12	7,89	7,28	7,78	**7,65**	**0,27**
Layers	**Sample 4**	**Sample 5**	**Sample 6**	**Average**	**Std. dev.**
6	6,51	6,05	6,45	**6,34**	**0,20**

Table 7: Final elongation (mm) of GFRE samples

These results are not as good as expected due to the lack of precision of the machine used to perform the experiments. Final elongation values should be lower than the values obtained. Therefore, the longitudinal strain is higher than expected and the Young's modulus is lower than expected.

3.1.1.3. Longitudinal strain (-)

The strain is calculated with the following formula:

$$\boldsymbol{\varepsilon} = \frac{\Delta \boldsymbol{L}}{\boldsymbol{L_0}} \quad \textbf{(3.1)}$$

ε = strain experienced by the composite sample
ΔL = final elongation of the composite sample
L_0 = initial length of the composite sample

As stated before, the length of the longitudinal axis of our composite is 226 mm, but we have to take into account that 25 mm of the sample were clamped between the UTM clamps, so we just have to take into account 180 mm of initial length.

Layers	Sample 1	Sample 2	Sample 3	Average	Std. dev.
12	0,044	0,040	0,043	**0,043**	**0,001**
Layers	**Sample 4**	**Sample 5**	**Sample 6**	**Average**	**Std. dev.**
6	0,036	0,034	0,036	**0,035**	**0,001**

Table 8: Longitudinal strain (-) of GFRE samples

Below, the same values are shown but in percentage:

Layers	Sample 1	Sample 2	Sample 3	Average	Std. dev.
12	4,38%	4,04%	4,32%	**4,25%**	**0,15%**
Layers	**Sample 4**	**Sample 5**	**Sample 6**	**Average**	**Std. dev.**
6	3,62%	3,36%	3,58%	**3,52%**	**0,11%**

Table 9: Longitudinal strain (%) of GFRE samples

3.1.1.4. UTS (MPa)

Stress is calculated following this formula:

$$\boldsymbol{\sigma = \frac{F}{A}} \tag{3.2}$$

σ = stress applied to the composite sample
F = maximum force supported by the composite sample
A = cross-sectional area of the composite sample

As mentioned above, the force is obtained from the data provided by the UTM tests. The area is obtained from the dimensions of the hand-made composites, so the area is as follows:

Layers	**Area (mm^2)**
6	30,48
12	63,50

Table 10: Area of the different samples of GFRE according to the layers

Layers	**Sample 1**	**Sample 2**	**Sample 3**	**Average**	**Std. dev.**
12	154,79	114,69	148,83	**139,44**	**17,67**
Layers	**Sample 4**	**Sample 5**	**Sample 6**	**Average**	**Std. dev.**
6	179,09	147,70	164,38	**163,72**	**12,82**

Table 11: UTS (MPa) of GFRE samples

3.1.1.5. Young's modulus (GPa)

The Young's modulus is calculated also from the data provided by the UTM and the data calculated in the previous sections: 3.1.1.3 and 3.1.1.4, stress and longitudinal strain, respectively.

This parameter can be calculated in two different ways:

1- Computing the slope of the linear region:

$$\boldsymbol{E = \frac{\sigma_2 - \sigma_1}{\varepsilon_2 - \varepsilon_1}} \tag{3.3}$$

E = Young's modulus for composite sample
σ_1 , σ_2 = two points of stress supported by the composite sample
ε_1 , ε_2 = two points of strain experienced by the composite sample

2- Using the Hooke's law:

$$\boldsymbol{E = \frac{\sigma_y}{\varepsilon_y}} \tag{3.4}$$

E = Young's modulus for composite sample
σ_y = yield stress
ε_y = strain corresponding to the yield stress

In fact, Eq. 3.3 and Eq. 3.4 are the same equation, but Eq. 3.3 uses any two points and Eq. 3.4 uses the point (0,0) as the first point (ε_1 , σ_1) and the point where it is assumed that finishes the linear part as the second point (ε_2 , σ_2). The handicap of the second option is that it only works in a Stress-Strain ideal curve. It means that when performing experiments, as in this case, Eq. 3.4 may give wrong results because the curve obtained is not completely linear (see Fig. 21). Therefore, the different Young's modulus calculated in this section have been calculated computing the slope of the linear region.

Layers	**Sample 1**	**Sample 2**	**Sample 3**	**Average**	**Std. dev.**
12	4,48	5,76	5,06	**5,10**	**0,52**
Layers	**Sample 4**	**Sample 5**	**Sample 6**	**Average**	**Std. dev.**
6	4,27	5,14	5,59	**5,00**	**0,55**

Table 12: Young's modulus (GPa) of GFRE samples

The following plot shows the Force-Displacement behavior of all the samples of GFRE. Naturally, the samples made of 12 layers are more resistant to traction than the samples of 6 layers.

For a simple two-constituent composite (matrix and reinforcement) under a given applied load, a certain proportion of that load will be carried by the fiber and the remainder by the matrix. While the behavior of the material remains elastic, the proportion of matrix-reinforcement will be independent of the applied load.

This proportion represents an important characteristic of the material and depends on the volume fraction, shape, and orientation of the reinforcement, and on the elastic properties of both constituents. The reinforcement acts efficiently if it carries a relatively high proportion of the externally applied load. This can result in higher strength, as well as greater stiffness, because the reinforcement is usually stronger, as well as stiffer, than the matrix. Therefore, the larger volume fraction of reinforcement, the more resistant the final part will be.

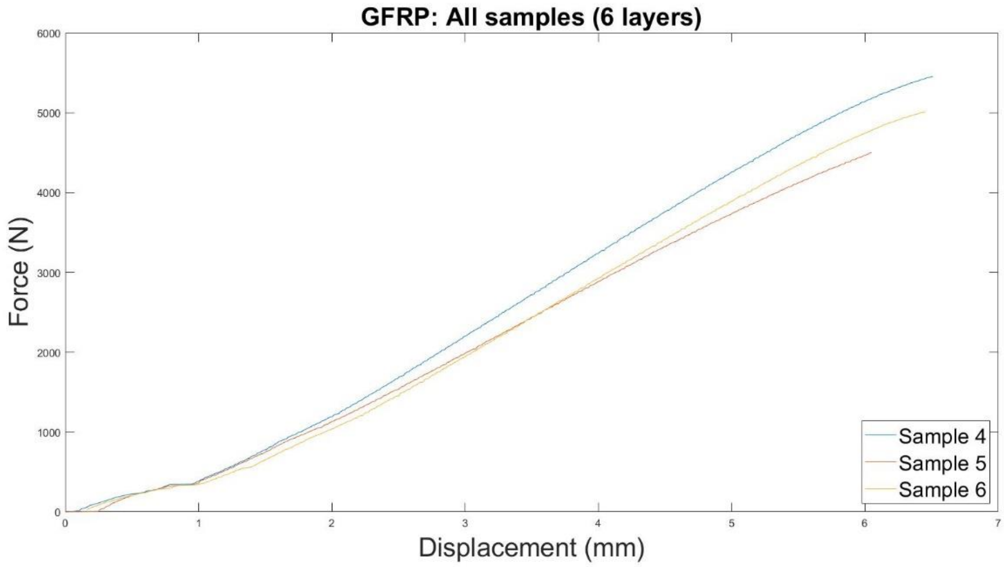


Figure 21: Force-Displacement of GFRP all samples

As it can be noticed from Fig. 21, the different lines corresponding to each sample are not completely linear. When doing experiments, it is very common to have some discrepancies since the experimental results tend to be worse than the theoretical ones. This happens because the specimen is getting slipped at the grips of the UTM.

3.1.2. CFRE composites

To calculate the results for the CFRE samples, we followed the same procedure as for the fiber-glass samples.

3.1.2.1. Ultimate force (N)

The obtained values are the following:

Layers	Sample 1	Sample 2	Sample 3	Average	Std. dev.
12	21.965,43	27.998,76	27.438,52	**25.800,90**	**2.721,72**
Layers	**Sample 4**	**Sample 5**	**Sample 6**	**Average**	**Std. dev.**
6	10.700,34	12.768,91	10.536,58	**11.335,28**	**1.015,93**

Table 13: Ultimate force (N) of CFRE samples

3.1.2.2. Final elongation (mm)

The obtained values are the following:

Layers	Sample 1	Sample 2	Sample 3	Average	Std. dev.
12	0,14	0,18	0,17	**0,16**	**0,02**
Layers	**Sample 4**	**Sample 5**	**Sample 6**	**Average**	**Std. dev.**
6	0,14	0,17	0,14	**0,15**	**0,01**

Table 14: Final elongation (mm) of CFRE samples

Contrary to the GFRE results, the final elongation values of CFRE are really valid. This is because these experiments were performed in a more accurate machine, not in EETAC campus, which, due to budgetary constraints, has never been calibrated since it was received more than 12 years ago.

3.1.2.3. Longitudinal strain (-)

The obtained values are the following:

Layers	Sample 1	Sample 2	Sample 3	Average	Std. dev.
12	0,001	0,001	0,001	**0,001**	**0**
Layers	**Sample 4**	**Sample 5**	**Sample 6**	**Average**	**Std. dev.**
6	0,001	0,001	0,001	**0,001**	**0**

Table 15: Longitudinal strain (-) of CFRE samples

Layers	Sample 1	Sample 2	Sample 3	Average	Std. dev.
12	0,076%	0,102%	0,096%	**0,091%**	**0,011%**
Layers	**Sample 4**	**Sample 5**	**Sample 6**	**Average**	**Std. dev.**
6	0,077%	0,093%	0,078%	**0,083%**	**0,007%**

Table 16: Longitudinal strain (%) of CFRE samples

3.1.2.4. UTS (MPa)

Now, the area used to calculate these values is different than with the GFRE.

Layers	Area (mm^2)
6	36,83
12	68,58

Figure 22: Area of the different samples of GFRE according to the layers

The obtained values are the following:

Layers	Sample 1	Sample 2	Sample 3	Average	Std. dev.
12	320,29	408,26	400,10	**376,22**	**39,69**
Layers	**Sample 4**	**Sample 5**	**Sample 6**	**Average**	**Std. dev.**
6	290,53	346,70	286,09	**307,77**	**27,58**

Table 17: UTS (MPa) of CFRE samples

3.1.2.5. Young's modulus (GPa)

The Young's modulus values are the following:

Layers	Sample 1	Sample 2	Sample 3	Average	Std. dev.
12	420,73	401,37	418,56	**413,55**	**8,66**
Layers	**Sample 4**	**Sample 5**	**Sample 6**	**Average**	**Std. dev.**
6	375.96	373,47	365,14	**371,53**	**4,63**

Table 18: Young's modulus (GPa) of CFRE samples

The following picture shows the Force-Displacement behavior of all samples during all the process of traction. As we can see, the samples made of 12 layers are more resistant than the samples of 6 layers, because the more layers a sample has, the more resistant it is. The detailed explanation is the same as in fiber-glass samples.

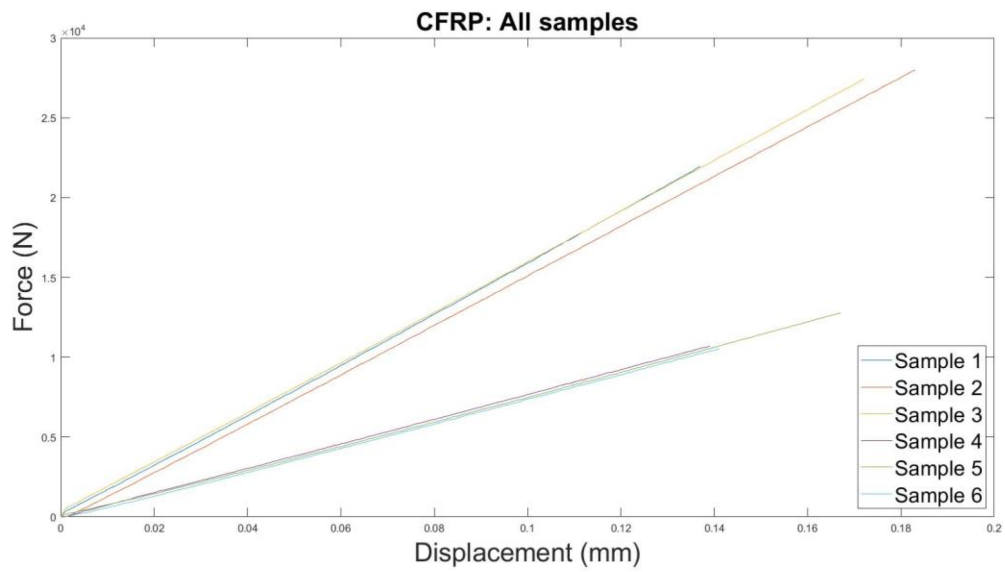


Figure 23: Force-Displacement of CFRP all samples

Finally, in Table 19, it is shown the average percentage increase of each mechanical property calculated in this section between the carbon and the glass fiber samples.

	Mechanical properties	**Carbon vs Glass**
12 layers	**Ultimate force**	177,41%
	Final elongation	-97,86%
	Longitudinal strain	-97,86%
	UTS	169,81%
	Young's modulus	8.005,75%
6 layers	**Ultimate force**	127,15%
	Final elongation	-97,65%
	Longitudinal strain	-97,65%
	UTS	87,99%
	Young's modulus	7.328,14%

Table 19: Comparison of mechanical properties of carbon fiber vs glass fiber samples

It is observed that the ultimate force, the UTS and the Young's modulus have a positive percentage increase, it means that CFRE have higher values of these properties than GFRE. It is noticed also that the percentage increase of the Young's modulus is considerably higher than the one of the UTS and the ultimate force. As we stated in section 3.1.1.2, due to the lack of accuracy of the equipment used to perform the tests, the values of final elongation are significantly worse than expected and consequently the Young's modulus of CFRE is much bigger than the one of GFRE. Moreover, the percentage increase of ultimate force and UTS is the same, this is because both parameters are directly proportional and as expected, CFRE have bigger values than GFRE.

On the other hand, it is seen that the percentage increase of the longitudinal and the final elongation is negative which confirm us that CFRE reaches lower values of deformation than GFRE because it is stiffer and stronger. Additionally, both values are equal, this happens because these two parameters are directly proportional, as happened with the ultimate force and the UTS.

3.2. Model results

Through an appropriate software as it is the *Abaqus CAE*, some relevant data have been obtained in order to analyze the behavior of the samples by means of numerical simulations and to validate these numerical results with the obtained experimental results.

Following the methodology described in section 2.2 and after introducing the input parameters specified in *Abaqus CAE*, we have obtained the following images of the stress distribution of each scenario.

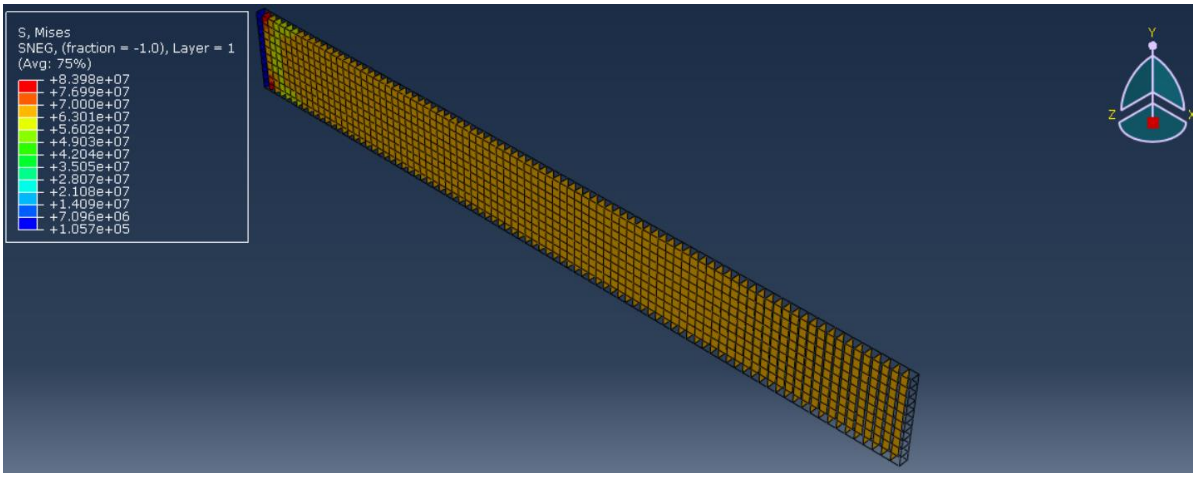


Figure 24: 6-layers sample of GFRE

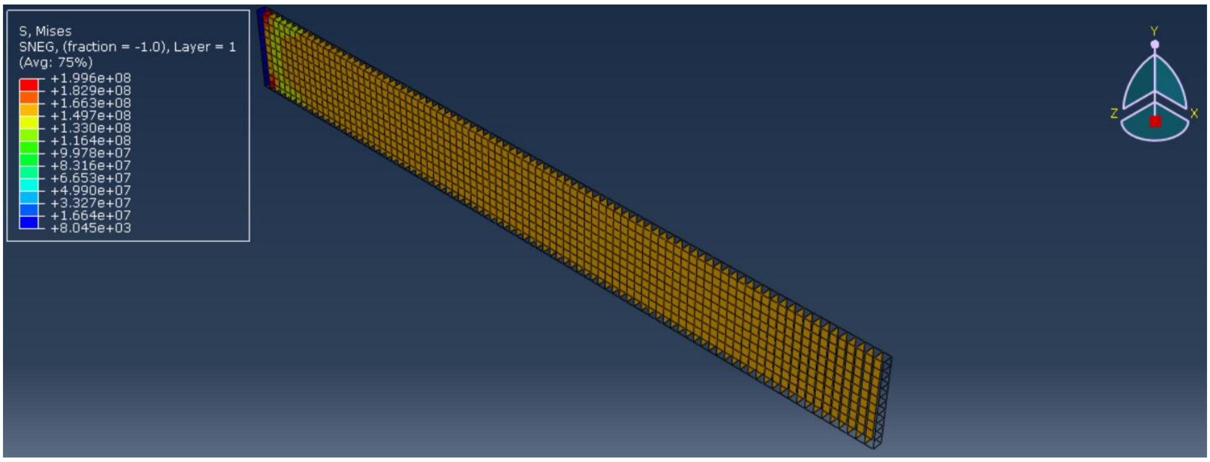


Figure 25: 6-layers sample of CFRE

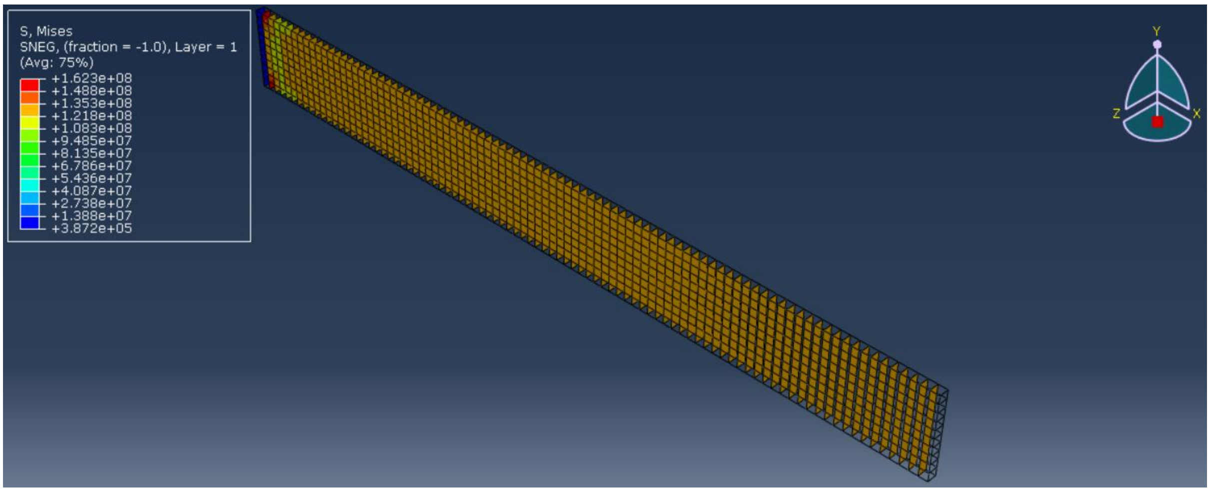


Figure 26: 12-layers sample of GFRE

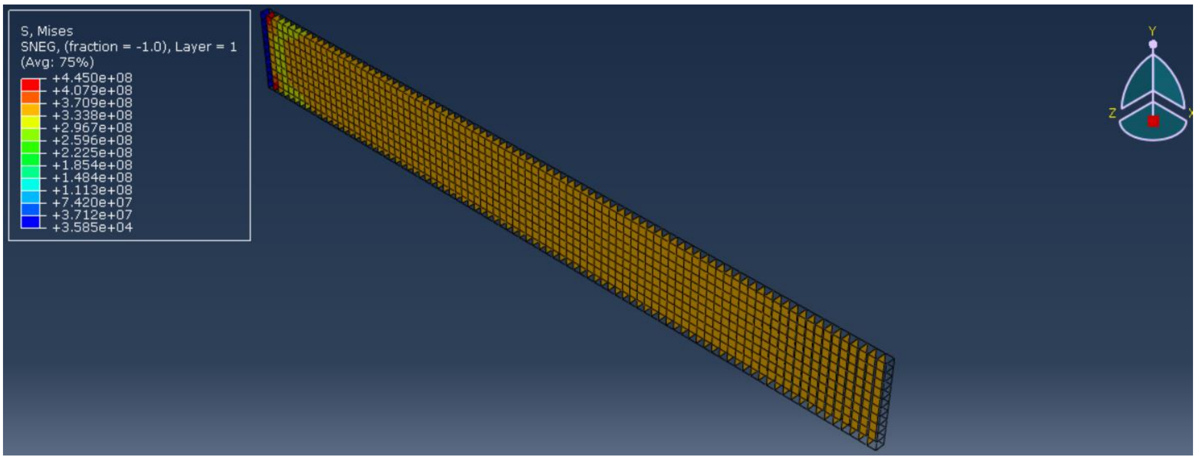


Figure 27: 12-layers sample of CFRE

Additionally, the ultimate force (N) for each scenario has been obtained. Therefore, it has been possible to compare the force results of the experimental part and the numerical part. As it can see in Table 20, the results obtained for both methodologies are very similar, with acceptable relative errors.

	CFRE		GFRE	
Nº of layers	**12**	**6**	**12**	**6**
Experimental results	25.800,90	11.335,28	9.300,67	4.990,24
Model results	25.889,00	11.613,10	9.259,58	4.838,16
Relative error	**0,34%**	**2,45%**	**0,44%**	**3,05%**

Table 20: Relative error between experimental results and numerical results

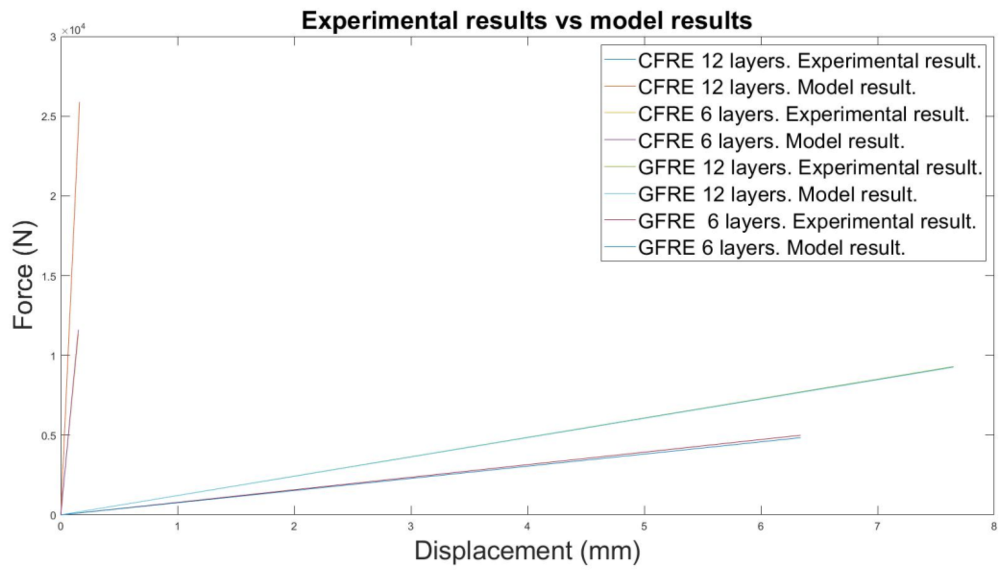


Figure 28: Comparison between experimental results and model results of all simulated samples

The relative error between both methods probably happens because the samples were made manually with a high probability of errors. It could also occur because of the lack of accuracy of the UTM. Maybe this error could be diminished performing the experimental tests with other more accurate equipment and other manufacturing process. Anyway, both results determine the same behavior for the CFRE samples and the GFRE samples. As demonstrated with the experimental results, this methodology also proves that CFRE have better mechanical properties than GFRE and are preferable if the cost is secondary. As it can be noticed in Fig. 28, CFRE is stiffer and stronger than GFRE, being this last one the more ductile of both.

CHAPTER 4. DISCUSSION

Chapter 4 will be focused on analyzing the resulting differences in the mechanical properties of the composite, depending on the reinforcements used to manufacture the samples, based on the experimental and numerical model results. The final aim of this chapter is to confirm whether the carbon-fiber samples have better mechanical properties than the glass-fiber samples, and those which are the best candidates to be used in the aerospace industry.

As shown in Fig. 29, CFRP can support a bigger force than GFRP, as expected. After doing the average between all the samples tested, we can confirm that the carbon-fiber sample of thickness 2,7 mm supports a force of 25.801 N, bigger than the force supported by the same sample of glass-fiber: 9.301 N. With the samples of only 6 layers happens the same, carbon-fiber is stronger than glass-fiber.

The maximum force supported by the material divided by the area of the sample is the UTS, and consequently, the UTS is greater in carbon-fiber than in glass-fiber, being 338,60 MPa and 122,06 MPa, respectively, for 12 layers samples. As can be observed in Fig. 29, CFRP samples break when the material arrives to its maximum force, that corresponds to its maximum stress or UTS, apparently without experiencing any plastic deformation. Thus, its yield stress corresponds also to its UTS. Contrary, GFRP samples apparently experience a slight level of plastic deformation, since the final part of the stress-strain plot is not linear but a bit curved.

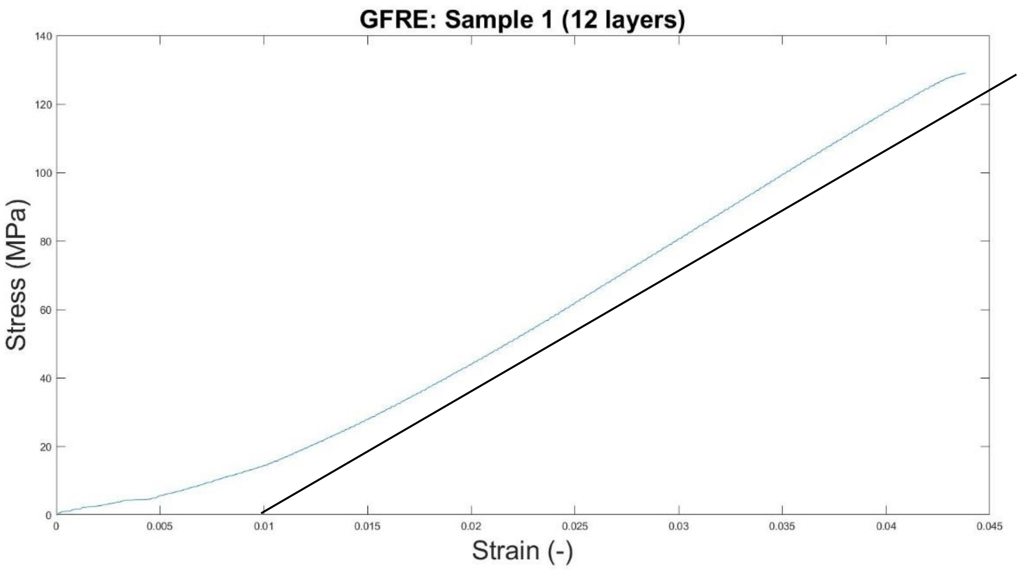


Figure 29: Stress-strain curve for a 12 layers samples of GFRE

To make sure that GRPE experience plastic deformation because of the non-linearity of its curve, we can apply the 0,2% criterion in its stress-strain curve. This criterion consists on drawing a line from the point (0,2%,0) parallel to the linear elastic zone with the same slope of E. As seen in Fig. 29, when applying this criterion, we obtain that any of the samples of GFRE tested experimentally experience plastic deformation, as the black line drawn does not end up crossing the stress-strain curve of the material. This means that the samples tested do not have a yield stress, they break without even experiencing a 0,2% of plastic or permanent or irreversible deformation.

Regarding the final elongation obtained for both types of fibers, we can confirm that CFRP reaches lower deformation values, while GFRP reaches higher deformation values, as expected. This happens because carbon-fibers are very stiff, so they can support large forces without experiencing very high deformations. Conversely, glass-fibers are more ductile and can absorb higher deformation energy, but with the handicap of being less stiff and breaking at lower forces. Consequently, the longitudinal strain experienced by CFRP is also lower than the experienced by GFRP, as the strain is given as the change in length, that is the elongation, divided by the original length.

Finally, the Young's modulus of CFRP is higher than that of GFRP. This fact is predictable because, as said before, carbon-fibers are very stiff in comparison with the glass-fibers, and the Young's modulus indicates mainly the stiffness of a material. The modulus is the slope of the stress-strain curve, so if the modulus is large, the material resists deformation strongly and, if the modulus is low, the material will deform more easily.

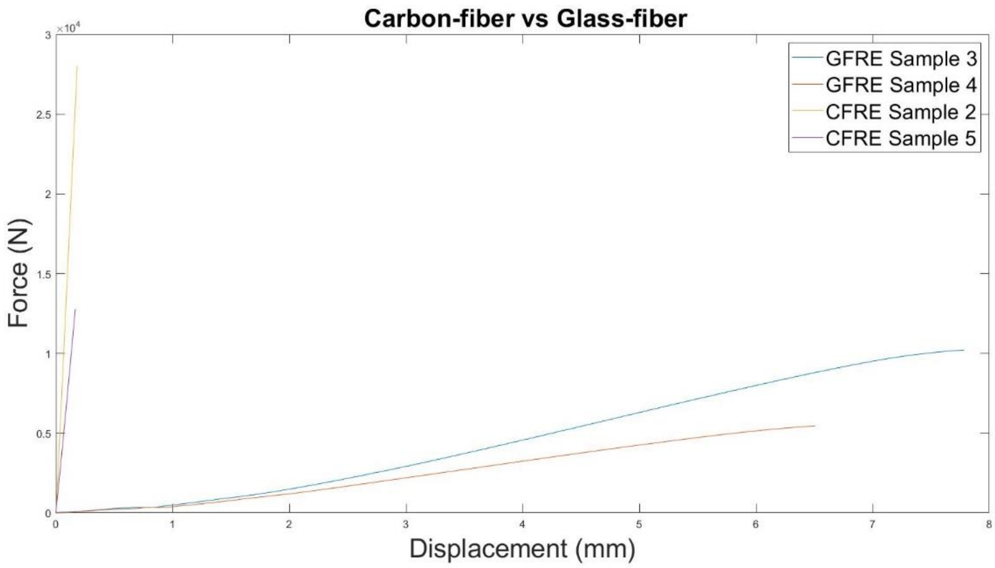


Figure 30: CFRE vs GFRE

CONCLUSIONS

The final aim of this thesis was to understand the behavior of different composite materials depending on the number of layers and the type of fibers used to make them. Through different appropriate experimental and numerical tools as the UTM and *Abaqus CAE*, it has been possible to obtain valuable data that provides us crucial information of the mechanical properties of our composites.

Glass-fibers are the most widely used type of reinforcement because of their electrical, strength, and corrosion-resistant properties, and relatively low cost. However, when there is a high priority of performance over cost, fiber-glass is not the most appropriate reinforcement to achieve good results. On the other hand, the more expensive carbon-fibers are the most prevalent fibers for critical or high-performance applications because of their very high strength and stiffness.

For aerospace applications, it is essential to use materials with high strength, high stiffness, high fracture toughness, and low weight. Therefore, carbon-fibers combined with high-performance matrices meet these criteria more closely than any other material. Aircraft control surfaces, full fuselages, helicopter rotor blades, wind turbine blades, and aircraft structural parts are some examples of where carbon-fibers are used in this huge sector. Summarizing, we can confirm that carbon-fiber composites are more suitable to aerospace applications than glass-fiber composites, when the cost is secondary.

Regarding the objectives, the results have proved what we expected after doing a deep research of what means material composites for aerospace industry. However, I realized that, when doing the experimental part of this thesis, if another manufacturing technique could be used, the experimental results would be much better than the ones obtained and would be much closer to the theoretical results.

Composites materials are relatively new materials that have not been used extensively until the last decades, so the lack of long, extensive studies in this regard can generate complications when choosing the materials of the compound. For this reason, as future work, several different tests could be done, for analyzing other mechanical properties and/or other different reinforcement and matrix materials. This may allow finding new materials that can be crucial for the aerospace industry.

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APPENDICES

TÍTOL DEL TFG: Analysis of different mechanical properties of composites and design of a hands-on activity for Bachelor's degree

TITULACIÓ: Grau en Enginyeria d'Aeronavegació

AUTOR: Aïna Nicolau Pérez

DIRECTOR: Jose Ignacio Rojas Gregorio

CO-DIRECTOR: Siddharth Pitta

DATA: 11 de juliol de 2019

APPENDIX A. ADDITIONAL INFORMATION

TYPES OF MATERIALS

There are different types of materials and they can be classified as follows:

- **Metals**

These materials are composed of one or more metallic elements (such as iron, aluminum, gold…) or non-metallic elements in relatively small amounts (such as oxygen, nitrogen, carbon…).

Regarding mechanical properties, metals are rigid and strong, but they are ductile (i.e., able to undergo deformation without breaking), so they are also resistant to fracture. Moreover, metallic materials are good conductors of electricity and heat, have high density (in comparison to the ceramics and the polymers), have a high capacity for reflection of light and some of them have desirable magnetic properties.

- **Ceramics**

Ceramic materials are made of metallic or non-metallic elements, such as oxides, nitrides and carbides.

With respect to mechanical properties, ceramics have some characteristics comparable to metals: they are relatively rigid and strong. Moreover, they are very hard materials. Contrary, they are extremely fragile (i.e., easily broken or destroyed). Therefore, in these materials the lack of ductility predominates.

In addition, ceramics are not good conductors of electricity; they have low electrical conductivities but are more resistant to high temperatures and hard environments than metals and polymers. Otherwise, ceramics may be transparent, translucent or opaque and some of the oxide ceramics have magnetic behavior.

- **Polymers**

Polymers include the familiar plastic and rubber materials. A polymer is a chemical, natural or synthetic compound formed by polymerization and consisting essentially of repetitive structural units. They come mainly from petroleum (mixture of hydrocarbons), natural gas and carbon.

Relating to mechanical behavior, polymers are not as rigid or as strong as these metals or ceramics. Nevertheless, based on their low densities, many times their stiffness and strength on a per mass basis are comparable to the metals and ceramics.

Furthermore, polymers are ductile and pliable (i.e., easily flexible without breaking or cracking), which means they are easily formed into complex shapes. In general, they are relatively inert chemically and non-reactive in many environments. One major drawback of the polymers is their tendency to soften and/or decompose at modest temperatures, which, in some instances, limits their use. Furthermore, they have low electrical conductivities and are nonmagnetic.

TYPES OF RESINS

- **Thermosets**

Thermosets are resins that are usually liquid (or easily melted solids) at room temperature. These resins are introduced into specific molds whereby heating process, their molecules form bonds or crosslinks. After the polymer material has been heated and the crosslink bonds formed, the thermoset material cannot be remolded, heated or melted again.

Some of the common thermosets include:

Epoxies: most widely used, best properties for primary structures, principal resin type in current graphite production use.

Bismalemides: good structural properties, intermediate temperature resistance, alternative to epoxy.

Phenolics: used in secondary structures, cabin interiors, primary with glass fibers.

Unsaturated Polyester: not for aerospace, used for industrial applications because of low cost.

Cyanate Esters: not for aerospace use.

- **Thermoplastics**

Thermoplastics are resins that are solids at room temperature. These resins can be reheated, remolded, and cooled as necessary without causing any chemical changes so the thermal environment of thermoplastic resins is a consideration in its use. If the temperature is too high, the product could undesirably lose other key properties.

As a result of these physical and chemical properties, thermoplastic materials have low melting points while thermoset products can withstand higher temperature without loss of its structural integrity.

Some of the common thermoplastics include polyethylene, nylon, polycarbonate, acrylic and polypropylene.

TYPES OF COMPOSITES DEPENDING ON THE MATRIX

- **Metal-matrix composites (MMC)**

These materials have a very low weight, high strength, high specific resistance and stiffness, and consequently, have a higher Young's modulus than other materials. It is important to remark that plastic at temperatures above 200ºC is degraded and here is the importance to use metal at these temperature values. MMC have high thermal influence behavior and can operate in extreme environments. Moreover, they have a very good damping capacity.

On the other hand, these materials have low fracture tenacity, and, in some situations, it is needed the use of special fibers to avoid fiber-matrix chemical reaction at high temperatures. Another disadvantage is that MMC have very high fabrication costs and nowadays there is not a lot of information about their behavior in service.

Three large groups can be classified according to the type of reinforcement incorporated:

  - Discontinuous and continuous reinforced fibers.
  - Large-particles or dispersion-strengthened particle-reinforced.
  - Structural.

An example of these materials is aluminum alloys with boron fiber reinforcements.

- **Ceramic-matrix composites (CMC)**

This type of composites has an enormous complexity in behavior and manufacturing. CMC have better mechanical properties as the resistance or the tenacity than the traditional ceramics, especially in low temperatures which is a good point to use ceramic for structural applications. As MMC, these are also classified according to the type of reinforcements used:

  - Discontinuous and continuous reinforced fibers.
  - Large-particles or dispersion-strengthened particle-reinforced.
  - Structural.

An example of these materials is the combination of reinforcing fibers with ceramic matrices as silicium carbide and those of aluminum oxide. Another case is the combination of discontinuous fibers or particles with a reinforcement of needles silicon carbide ceramics.

DIFFERENT TYPES OF COMPOSITES DEPENDING ON THE REINFORCEMENT

- **Particle-reinforced composites**

In most composite materials, the dispersed phase is harder and more resistant than the matrix. The reinforcing particles tend to restrict the movement of the matrix around each particle. The matrix transfers part of the applied effort to the particles, which support a part of the load. Thus, the degree reinforcement composites, or improvement of mechanical behavior depends on strong bonding at the matrix-particle interface. Large-particle and dispersion-strengthened composites are the two sub-classifications of particle-reinforced composites.

  - Large particle:

A large-particle is a type of particle-reinforced composite wherein particle-matrix interactions cannot be treated on an atomic or molecular level; they must be treated in a macromolecular level. The particle reinforced the matrix phase. For effective reinforcement, the particles should be small and evenly distributed throughout the matrix. Large-particle composites are used with all three material types (metals, polymers, and ceramics). Some polymeric materials to which fillers have been added are really large-particle composites. An example of large particle is concrete, which is composed of cement (the matrix) and sand and gravel (the particles).

The particles can have quite a variety of geometries, but they should be of approximately the same dimension in all direction (equiaxed) to avoid orientations with greater fragility. The volume fraction of the two phases influences the behavior; mechanical properties are enhanced with increasing particulate content.

  - Dispersion-strengthened:

Dispersion-strengthened refers to materials where very small particles (usually smaller than 0.1 µm) of a hard yet inert phase are uniformly/ homogenously dispersed within a load–bearing matrix phase. Due to the obstruction produced by those small particles, the material becomes harder because dislocations cannot move so easily. They have better resistance to creep than metals and some alloys. The dispersed phase may be metallic or nonmetallic, and oxide materials are often used.

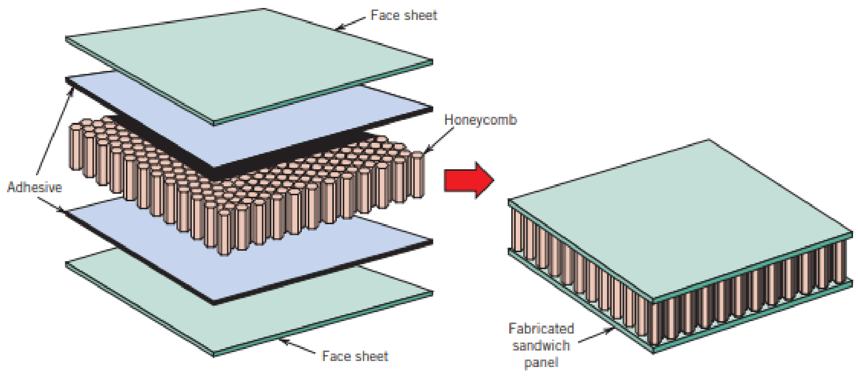
- **Structural composites**

    - Sandwich panels

This structure is a type of laminate composite. A sandwich panel consists of two thin and resistant panels that are separated by and adhesively bonded to a thicker and lightweight core. This combination results on a final product that is very thin, light, rigid and resistant.

The panels are made of a relatively stiff and strong material, typically aluminum alloys, fiber-reinforced plastics, titanium, steel, or plywood; they impart high stiffness and strength to the structure and must be thick enough to withstand tensile and compressive stresses that result from loading.

The core material is lightweight, and normally has a low modulus of elasticity. Its function of keeping the outer panels separated, providing thermal insulation and transmitting the cutting forces from one layer to the opposite. Core materials typically fall within three categories: rigid polymeric foams (i.e., epoxy, polyurethanes), wood (i.e., balsa wood), and **honeycombs.** Core compounds allow to improve the mechanical properties, but without an excessive increase in weight. They also improve the thermal and acoustic insulation.



Picture A.1: Fabricated sandwich panel [4]

- **Honeycomb core**

The honeycomb core is mainly made of metal, glass fibers, carbon or aramid, paper or composites. The shape of this core follows a geometric pattern of hexagonal cells. The rows are joined with adhesive or adherent sheets.

The main objective of honeycomb core is to achieve structures with the minimum weight and a considerable flexibility. For example: radomes, fuselage panels, leading edge and exit. There are also non-metallic panels that are easier manageable, more comfortable and machinable, free of fatigue and withstand vibrations.

USE OF COMPOSITES IN AEROSPACE STRUCTURES

We can summarize the features of aircraft structure in the following table:

Requirement	Applicability	Effect
• Light-weight	All Aerospace Programmes	♦ Semi-monocoque construction * Thin-walled-box or stiffened structures ♦ Use of low density materials: * Wood * Al-alloys * Composites ♦ High strength/weight, High stiffness/weight
• High reliability	All Aerospace Programmes	♦ Strict quality control ♦ Extensive testing for reliable data ♦ Certification: Proof of design
• Passenger safety	Passenger vehicles	♦ Use of fire retardant materials ♦ Extensive testing: Crashworthiness
• Durability-Fatigue and corrosion	Aircraft	♦ Extensive fatigue analysis/testing * Al-alloys do not have a fatigue limit!!! ♦ Corrosion prevention schemes ♦ Issues of damage and safe-life, life extension
Degradation: Vacuum Radiation Thermal	Spacecraft	♦ Extensive testing for required environment ♦ Thin materials with high integrity
• Aerodynamic performance	Aircraft Reusable spacecraft	♦ Highly complex loading ♦ Thin flexible wings and control surfaces * Deformed shape-Aeroelasticity * Dynamics ♦ Complex contoured shapes * Manufacturability: N/C Machining; Moulding
• Multi-role or functionality	All Aerospace Programmes	♦ Efficient design ♦ Use: composites with functional properties
• Fly-by-wire	Aircrafts, mostly for fighters but also some in passenger a/c	♦ Structure-Control Interactions * Aero-servo-elasticity ♦ Extensive use of computers and electronics * EMI shielding
• Stealth	Specific Military Aerospace Appl	♦ Specific Surface and Shape of aircraft * Stealth coatings!!!
• All-weather operation	Aircraft	♦ Lightning protection, erosion resistance

Table A.1: Features of aircraft structure [5]

ARAMID FIBERS

- **Aramid fiber (Kevlar, AFRP, AFRE, etc.)**

Aramid fiber is a class of heart-resistant and strong synthetic fibers. They are used in aerospace and military applications, for ballistic rated body armor fabric and ballistic composites and in bicycle tires.

Aramid fiber has a higher strength and stiffness than glass fibers and have better ultimate tensile strain and energy absorption than carbon fibers. In addition, it has good fatigue properties, good toughness and impact resistance and very good tensile characteristics but poor in compression and transverse and have a low density.

RESINS IN THE AEROSPACE SECTOR

- **Vinylester**

We can classify vinylester resin as an intermediate resin between epoxy and polyester. It has good physical and mechanical properties, as epoxies; but its curing cycle is relatively short, as polyester resins.

Vinylester has a 1/3 part of the strength of epoxy and adheres poorly to carbon and aramids. This resin is used primarily for glass fibers but also for carbon fibers.

Vinylester is used mostly in cosmetic applications, since it should never be used for carbon or aramid fibers if strength is primary.

- **Polyester**

This resin is the cheapest one, it has a poor bounding capability and it should be never used for any structural carbon or aramid work. Polyester typically works well on glass fiber. These resins have a low rigidity and resistance. During hardening they tend to contract between 6 and 10%.

MANUFACTURING PROCESSES

The most significant manufacturing processes are the following: [6,7]

- Contact:

Spray-up molding

In spray-up, the fibers are chopped and sprayed into the mold simultaneously with the resin. It is also assumed that the fibers are sprayed into the molt in essentially a manual process. This method is used when the size and the design of the composite wanted is enough simple and it is possible to spray the resin and the reinforcement easily with a good uniformity.

In difference with hand lay-up method, spray-up is not a good choice for small and complex shapes. However, the main advantage of this method is simply the speed with which the fiber and resin can be applied to the mold. Moreover, if structural requisites are not very demanding, this method can be used to increase production line. In this process, thickness and consistency are controlled.

Furthermore, spray-up requires a special spraying equipment, the variety of resins is more limited, it is impossible to control the direction of the fibers, there is high air pollution because of spraying the resin and the operator needs even a higher skill level than in the lay-up method.

In this method, the fibers are brought into the chopper as roving and then chopped so that they fall into the stream of resin just after the nozzle. This means that the chopped fibers are entrained with the resin and together are sprayed into the mold. The operator sprays the resin and the fibers into the mold. Some training for the operator is required because the uniformity of fiber placement is critical to the performance of the composite. After the fibers and resin are sprayed into the mold, a roller is used to make sure the rein fully wets the fiber. Therefore, even spray-up uses manual labor as part of the process.

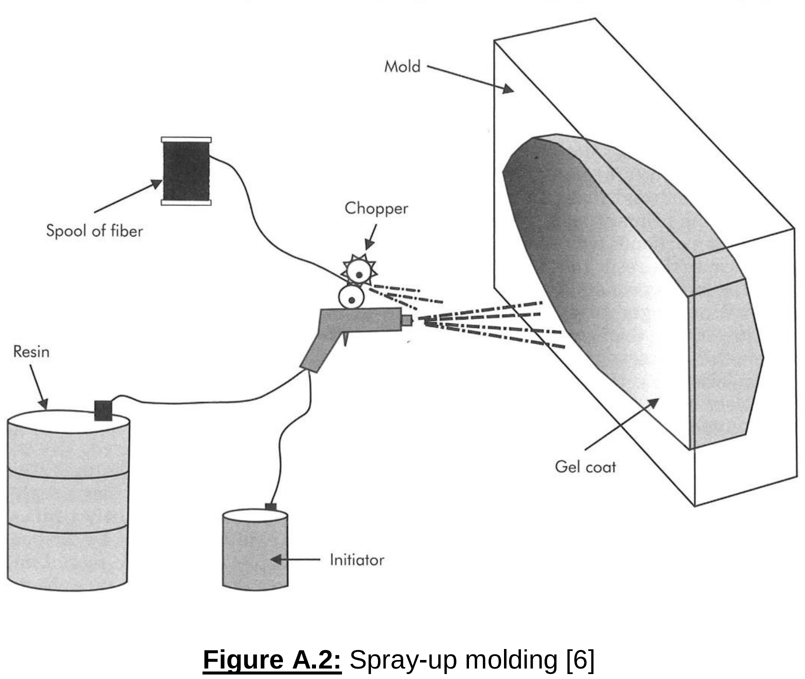


Figure A.2: Spray-up molding [6]

Prepeg lay-up (fiber placement)

Prepeg lay-up is born of the problems and difficulties that lay-up and spray-up molding methods presents:

- The orientation of the fibers to the desired direction.
- The optimization of the amount of fibers to achieve the best mechanical properties.
- The control the fiber/resin ratio.
- Obtaining full fiber wet-out.
- Difficulty in reducing the void content.
- The mixture of the resin and the hardener including emission and toxicity problems.

A prepeg is a common term for reinforcing fabric or fiber which has been previously impregnated with a resin with curing retardants, arranged on paper to facilitate handling.

The prepeg is delivered ready to lay into a mold to the manufacturer, who fully cures the product without having to add any addition resin or hardener. They must be stored at low temperatures to avoid the further curing and cross-linking of the resin matrix which occurs at room temperature.

Two systems are available for placing the prepeg in the mold: manual lay-up and automatic lay-up.

The manual lay-up technique consists on laying plies of precut prepeg into a mold. Firstly, sufficient material is cut from the roll of prepeg to be able to make the final composite. Then, the sheet of prepeg is placed on a special cutting table where it is cut to the shapes required in the lay-up and finally, the pieces are placed into the mold. Each prepeg piece is placed carefully making sure the alignment of the sheet is exactly according to the specification of the composite part's design. After the first layer has been placed into the mold, subsequent layers are placed on top of the first.

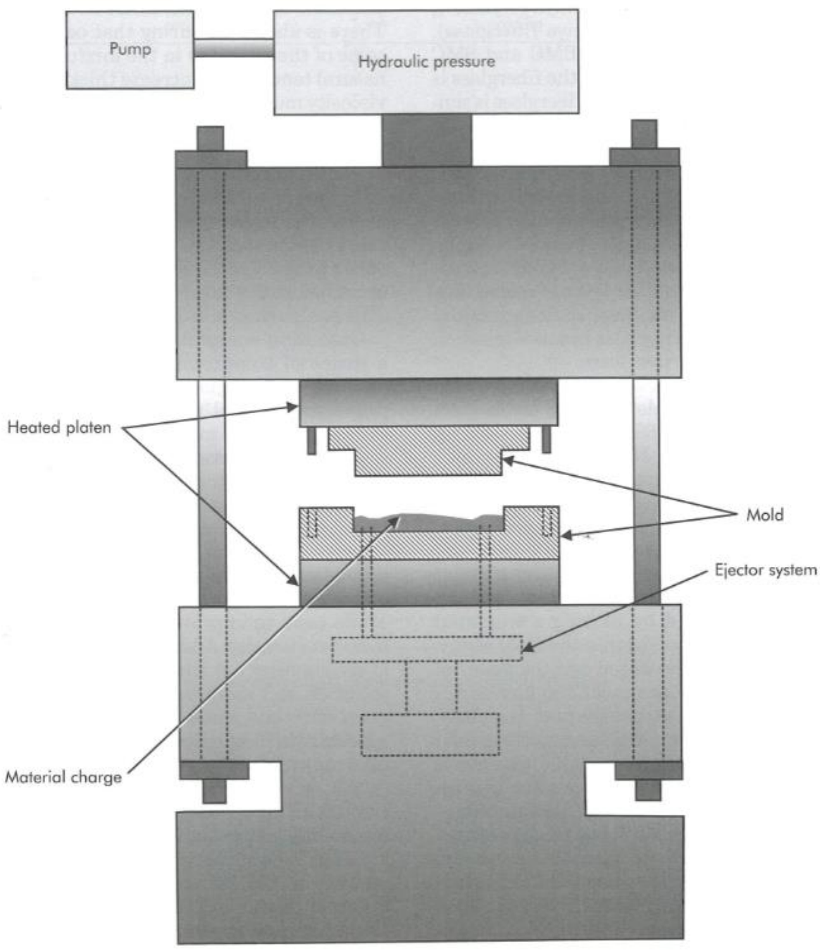
On the other hand, the automatic lay-up technique begins when a roll of prepeg material is mounted on the payout drive of a tape-laying machine. These machines are large and expensive, but they can accurately and quickly lay down plies of a prepeg.

The machine has a gantry-mounted head that applied and cuts the prepeg. The machine also indexes the area within which the prepeg is to be applied. Then, the machine presses the leading edge of the strip of prepeg onto the mold surface in order to obtain the specified design. The machine then moves along a straight line and feeds and presses the prepeg onto the mold while simultaneously lifting the paper backing. When the edge of the mold is reached, the head cuts the prepeg strip at the proper angle ant hen lifts and moves to the correct position to begin laying the next trip. This process is repeated until the entire laminate has been laid.

The advantages of using this prepeg lay-up are the following:

- Control the orientation of the fibers and their location.
- Control the thickness of each ply.
- Control the fiber-resin ratio.
- Minimize the void content.
- Reduce internal stresses.
- Less mess, less waste and less curing time.

- <u>Compression molding:</u>



<u>Figure A.3:</u> Compression molding [6]

In this method, an amount of uncured resin and fibers are placed into the cavity of a matched mold in the open position. Then, we bring the male and female halves together to close the mold, so pressure is applied, and the composite material fills uniformly the cavity of the mold. While under pressure, the material is heated so that it cures.

Compression molding requires high pressures and consequently, the molds and presses are very large. The presses allow rapid mold cycles and high-volume production. This technique is the best to reproduce part-to-part composites and the squeezing of the materials results in low void contents in the resulting parts.

Comparing this method with other composite molding processes, compression molding has low labor requirements.

Two different compression molding processes are differentiated:

- **Cold compression →** In this technique, the reinforcement is in the form of felt, so the fibers are oriented randomly. Consequently, the structural capacity decreases. In terms of curing, the material is rapidly cured at room temperature.

- **Hot compression →** In this technique, the reinforcement is in the form of prepeg, so the curing time into the heated mold is faster than with cold compression. Hot compression leads to a major control of the orientation and the volume of the fibers as prepeg materials are used and consequently, the structural capacity increases.

- Pultrusion:

Pultrusion is a continuous, high-volume manufacturing process used to make parts that have continuous lengths and constant cross-section shapes (i.e., rods, tubes, beams, etc.).

The fibers are wetted by the resin and then are pulled through a heated die to form a part. The steel die performs to the desired shape and establishes the resin/fiber ratio. After that, the stock passes through a curing die where the material is finally formed. A pulling device is continuously pulling the formed material drawing the stock through the dies and also determining the production speed. Finally, the cut-off saw cuts the material to predetermined lengths.

This manufacturing technique involves a high cost equipment and it is very strict, as the products are limited to constant cross-sections. These disadvantages make pultrusion less widely practiced than other composites molding processes.

The cost per part and the productivity in terms of cycle time (easily automated) are the best of any composites manufacturing process. Thanks to these excellent parameters, pultrusion is a rapidly and economic method.

Between other advantages of this method there is the accurately control of the quantity of the resin applied. Structural properties of laminates can be very good as the fibers are very straight and fiber volume fractions are very high.

Another advantage of the pultrusion process is the ability to use a wide variety of different reinforcements. Contrary, this method does not allow a good control of the orientation of the fibers.

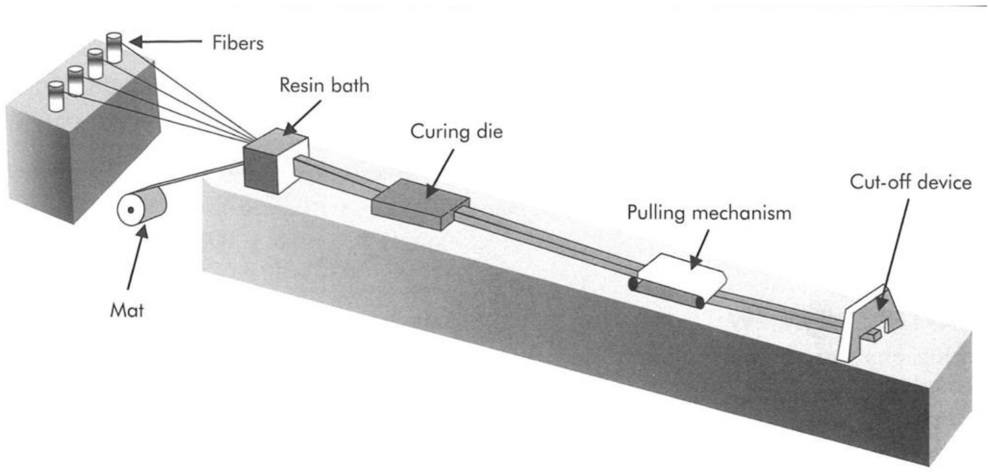


Figure A.4: Pultrusion technique [6]

- Filament winding:

Filament wilding is most important of the composites processes in terms of the number of users and the total number of parts made. Filament winding is popular with shell like components such as rocket motor casings for launch vehicles and missiles.

The fiber spools are mounted on a rack, called a creel, and then strands from many spools are gathered together and fed through a comb or similar alignment device so they make a band of fibers. The number of strands brought together determines the width of the band. The band then is impregnated in a resin bath. The resin is activated with an initiator or hardener, so it is only need heat and time to cure the part.

The fibers then go through a roller or wiper system to remove the excess resin and then through a ring or some other directing device called a payoff which directs the fibers onto a mandrel where will be wrapped by a lateral movement to achieve the desired thickness. The fibers are stressed on the mandrel.

Once the winding operation has been completed, the part is cured. Part can be cured at room temperature or in ovens or autoclaves and finally, the mandrel is removed. The final product is hollow.

This process is typically used to manufacture hollow shapes (usually cylindrical structures); such as pipes or tanks, because of the mandrel. However, by allowing the payoff head to move vertically or twist and rotate, complicated shapes can be made.

Filament winding is one of the fastest and most economic methods to manufacture composites. Fibers and resin are used in their lowest-cost forms. The needed elements as mandrels, machines and oven can be costly, but options allow many parts to be made simultaneously but the productivity is very high.

On the other hand, manpower is very effective as usually only one operator is needed per machine. Therefore, the cost of parts made by filament winding is about one-quarter to one-half the cost of parts made by manual lay-up.

In addition, with this method the resulting composites have very high strength-to-weight ratios as the continuous nature of the filament means that the strength and stiffness are excellent. A high degree of control over winding uniformity and orientation is achieved. Furthermore, with low speeds we can strictly control the void content increasing the mechanical properties of the resulting part.

Because of filament winding is automated, manufacturing efficiencies are easily obtained. However, an important disadvantage of this process is the limitation to make parts that are not much more varied in shape and complexity.

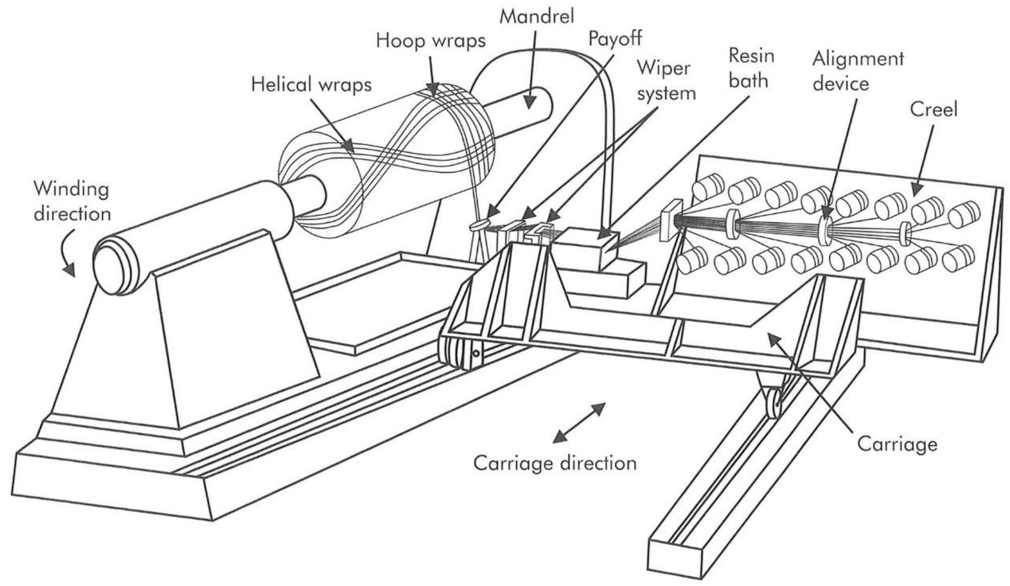


Figure A.5: Filament winding process [6]

- Resin infusion:

Resin infusion technologies are differentiated in three main groups:

- **Compound Injection (BMC and SMC)**
- **Resin Transfer Molding (RTM)**
- **Resin Injection Molding (RIM)**

All of the resin infusion technologies share come common features. In all of them the dry fiber preform is placed into a mold and the mold is closed. Then, resin is injected into the mold wetting the fiber preform. The resin is cured, the mold is opened, and the part is extracted.

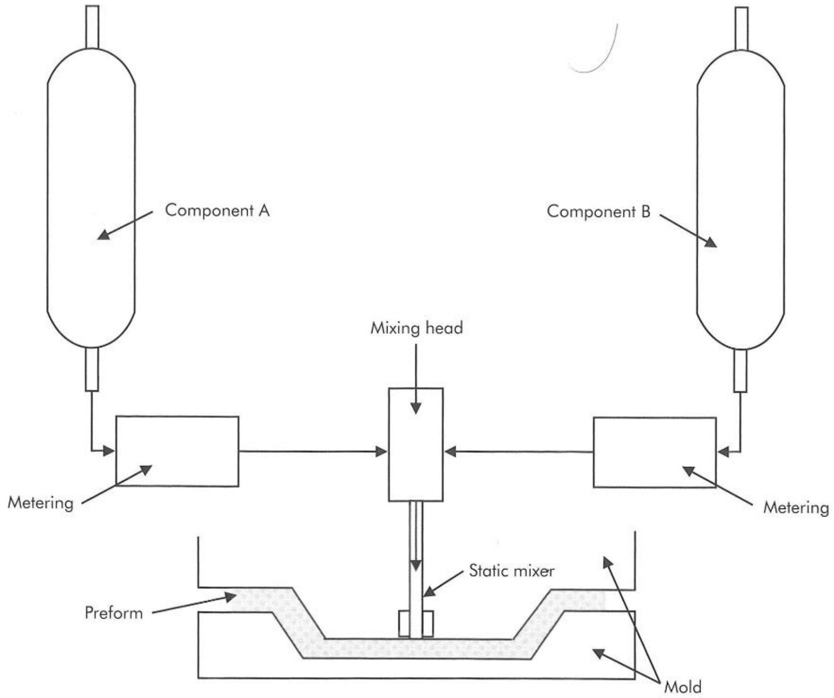


Figure A6: Basic resin infusion manufacturing technique [6]

BMC means Bulk Molding Compound and SMC means Sheet Molding Compound. Compound molding such as BMC and SMC are mixtures of resin (almost always polyester), fillers, fibers reinforcement (almost always fiberglass) and curing agents. In both BMC and SMC all the components necessary for complete curing of the part are mixed into the resin when the molding compound is made.

BMC is molded by placing a weighted amount of the material into the mold cavity. Then, the molds are closed, and the material fulfill the mold. Heat is applied by the molds to cure the part. Besides, SMC is molded by cutting off the proper amount of sheet from the roll of molding compound, removing the carrier film, and laying the sheet material into the mold.

On the other hand, resin transfer molding (RTM) is the process most widely used. It is a closed-mold process for manufacturing high performance composite components in medium volumes.

This process is similar to compression molding except that the mold is closed when the rein is injected. Molds typically consist of matched metal tools into which a dry fiber is inserted. The mold is then closed and clamped shut before pumping resin into the tool cavity to thoroughly wet-out the fibers. The tool will often be heated to assist with the curing of the resin. Once the resin is cured, the tool can be opened, and the part removed.

The combination of high clamping pressures (often achieved using a secondary press) and forcibly injecting the resin, makes it possible to achieve relatively high fiber volume fractions resulting parts with an excellent performance part (strength and quality).

The use of matched metal tools means that parts have a good surface finish, requiring minimal finishing. However, these tools are generally costly so there is a limitation when the production is low. In addition, the process can be very quick if a suitable reactive resin and a high injection pressure are applied. Depending on the size of the part cycle times of just a few minutes are obtained.

The mold does not require high expenses as the closed mold and mechanized resin handling make it a clean process with a low exposure levels for operators. In addition, an important advantage of this process is the possibility to place continuous fibers into the mold, so the molding operation is performed without moving the fibers. This method is used specially in components such as radomes.

Finally, RIM is a double-mold method. At first, the dry fibers are laid into a metal mold. The fiber volume is always around a 40% of the composite. A metal counter mold is then hydraulically pressed down over the composite object. Under high pressure (1.5 MPa) the catalyzed resin is injected into the mold and saturates the fibers. The mold is heated to cut down on cycle time.

Metal molds are more expensive than ordinary composite molds and have a very long service life. Meanwhile, RIM's short process time makes the process perfect for large production.

In this process, it is achieved a resulting part of an excellent strength and particularly excellent surface quality on both sides. It is also achieved a highly even quality and material thickness.

RTM and RIM surpasses BCM and at least equals SMC in mechanical performance. This is because the fibers do not need to move in the mold. The operational costs between both methodologies are similar but the material is slightly higher in RTM and RIM because it is difficult to add fillers. However, other costs such as the reduction in auxiliary equipment needed and the environmental aspect of those techniques often result in it being the lowest cost molding process.

APPENDIX B. CODE

```
%% Glass-fiber

sheet_1_glass = 'GFRP 3 mm S1';
xlRange_Specimen1_glass = 'A8:B1069'; %1st column: Displacement, 2nd
column: Force
subset_Specimen1_glass =
xlsread('Glass.xls',sheet_1_glass,xlRange_Specimen1_glass);
sheet_2_glass = 'GFRP 3 mm S2';
xlRange_Specimen2_glass = 'A8:B902'; %1st column: Displacement, 2nd
column: Force
subset_Specimen2_glass =
xlsread('Glass.xls',sheet_2_glass,xlRange_Specimen2_glass);
sheet_3_glass = 'GFRP 3 mm S3';
xlRange_Specimen3_glass = 'B10:C1111'; %1st column: Displacement,
2nd column: Force
subset_Specimen3_glass =
xlsread('Glass.xls',sheet_3_glass,xlRange_Specimen3_glass);
sheet_4_glass = 'GFRP 1,5 mm S4';
xlRange_Specimen4_glass = 'A6:B709'; %1st column: Displacement, 2nd
column: Force
subset_Specimen4_glass =
xlsread('Glass.xls',sheet_4_glass,xlRange_Specimen4_glass);
sheet_5_glass = 'GFRP 1,5 mm S5';
xlRange_Specimen5_glass = 'B4:C608'; %1st column: Displacement, 2nd
column: Force
subset_Specimen5_glass =
xlsread('Glass.xls',sheet_5_glass,xlRange_Specimen5_glass);
sheet_6_glass = 'GFRP 1,5 mm S6';
xlRange_Specimen6_glass = 'A5:B659'; %1st column: Displacement, 2nd
column: Force
subset_Specimen6_glass =
xlsread('Glass.xls',sheet_6_glass,xlRange_Specimen6_glass);

figure;
plot(subset_Specimen1_glass(:,1),subset_Specimen1_glass(:,2));
xlabel(['\fontsize{25}Displacement (mm)'])
ylabel(['\fontsize{25}Force (N)'])
title(['\fontsize{24}GFRP: Sample 1 (12 layers)'])
figure;
plot(subset_Specimen2_glass(:,1),subset_Specimen2_glass(:,2));
xlabel(['\fontsize{25}Displacement (mm)'])
ylabel(['\fontsize{25}Force (N)'])
title(['\fontsize{24}GFRP: Sample 2 (12 layers)'])
figure;
plot(subset_Specimen3_glass(:,1),subset_Specimen3_glass(:,2));
xlabel(['\fontsize{25}Displacement (mm)'])
ylabel(['\fontsize{25}Force (N)'])
title(['\fontsize{24}GFRP: Sample 3 (12 layers)'])
figure;
plot(subset_Specimen3_glass(:,1),subset_Specimen3_glass(:,2));
xlabel(['\fontsize{25}Displacement (mm)'])
```

```
ylabel(['\fontsize{25}Force (N)'])
title(['\fontsize{24}Glass-fiber sample'])
figure;
plot(subset_Specimen4_glass(:,1),subset_Specimen4_glass(:,2));
xlabel(['\fontsize{25}Displacement (mm)'])
ylabel(['\fontsize{25}Force (N)'])
title(['\fontsize{25}GFRP: Sample 4 (6 layers)'])

subset_Specimen5_glass(isnan(subset_Specimen5_glass))=0;

figure;
plot(subset_Specimen5_glass(:,1),subset_Specimen5_glass(:,2));
xlabel(['\fontsize{25}Displacement (mm)'])
ylabel(['\fontsize{25}Force (N)'])
title(['\fontsize{24}GFRP: Sample 5 (6 layers)'])
figure;
plot(subset_Specimen6_glass(:,1),subset_Specimen6_glass(:,2));
xlabel(['\fontsize{25}Displacement (mm)'])
ylabel(['\fontsize{25}Force (N)'])
title(['\fontsize{24}GFRP: Sample 6 (6 layers)'])

figure;
plot(subset_Specimen1_glass(:,1),subset_Specimen1_glass(:,2));
hold on
plot(subset_Specimen2_glass(:,1),subset_Specimen2_glass(:,2))
plot(subset_Specimen3_glass(:,1),subset_Specimen3_glass(:,2))
xlabel(['\fontsize{25}Displacement (mm)'])
ylabel(['\fontsize{25}Force (N)'])
title(['\fontsize{24}GFRP: All samples (12 layers)'])


figure;
plot(subset_Specimen4_glass(:,1),subset_Specimen4_glass(:,2));
hold on
plot(subset_Specimen5_glass(:,1),subset_Specimen5_glass(:,2))
plot(subset_Specimen6_glass(:,1),subset_Specimen6_glass(:,2))
xlabel(['\fontsize{25}Displacement (mm)'])
ylabel(['\fontsize{25}Force (N)'])
title(['\fontsize{24}GFRP: All samples (6 layers)'])

figure;
plot(subset_Specimen1_glass(:,1),subset_Specimen1_glass(:,2));
hold on
plot(subset_Specimen2_glass(:,1),subset_Specimen2_glass(:,2))
plot(subset_Specimen3_glass(:,1),subset_Specimen3_glass(:,2))
plot(subset_Specimen4_glass(:,1),subset_Specimen4_glass(:,2))
plot(subset_Specimen5_glass(:,1),subset_Specimen5_glass(:,2))
plot(subset_Specimen6_glass(:,1),subset_Specimen6_glass(:,2))
xlabel(['\fontsize{25}Displacement (mm)'])
ylabel(['\fontsize{25}Force (N)'])
title(['\fontsize{24}GFRP: All samples'])

%% Glass-fiber STRESS-STRAIN CURVE

sheet_1_GFRE = 'GFRP 3 mm S1';
```

```
xlRange_Specimen1_GFRE = 'D7:E1069'; %1st column: Stress, 2nd
column: Strain
subset_Specimen1_GFRE =
xlsread('Glass.xls',sheet_1_GFRE,xlRange_Specimen1_GFRE);

figure;
plot(subset_Specimen1_GFRE(:,2),subset_Specimen1_GFRE(:,1));
xlabel(['\fontsize{25}Strain (-)'])
ylabel(['\fontsize{25}Stress (MPa)'])
title(['\fontsize{24}GFRE: Sample 1 (12 layers)'])

%% Carbon-fiber

sheet_1_carbon = 'CFRE 3 mm S1';
xlRange_Specimen1_carbon = 'B3:C140'; %1st column: Displacement, 2nd
column: Force
subset_Specimen1_carbon = xlsread('CFRP
final.xlsx',sheet_1_carbon,xlRange_Specimen1_carbon);
sheet_2_carbon = 'CFRE 3 mm S2';
xlRange_Specimen2_carbon = 'C4:D187'; %1st column: Displacement, 2nd
column: Force
subset_Specimen2_carbon = xlsread('CFRP
final.xlsx',sheet_2_carbon,xlRange_Specimen2_carbon);
sheet_3_carbon = 'CFRE 2,7mm S3';
xlRange_Specimen3_carbon = 'C4:D176'; %1st column: Displacement, 2nd
column: Force
subset_Specimen3_carbon = xlsread('CFRP
final.xlsx',sheet_3_carbon,xlRange_Specimen3_carbon);
sheet_4_carbon = 'CFRE 1,5 mm S4';
xlRange_Specimen4_carbon = 'C3:D142'; %1st column: Displacement, 2nd
column: Force
subset_Specimen4_carbon = xlsread('CFRP
final.xlsx',sheet_4_carbon,xlRange_Specimen4_carbon);
sheet_5_carbon = 'CFRE 1,5 mm S5';
xlRange_Specimen5_carbon = 'C3:D170'; %1st column: Displacement, 2nd
column: Force
subset_Specimen5_carbon = xlsread('CFRP
final.xlsx',sheet_5_carbon,xlRange_Specimen5_carbon);
sheet_6_carbon = 'CFRE 1,5 mm S6';
xlRange_Specimen6_carbon = 'C4:D144'; %1st column: Displacement, 2nd
column: Force
subset_Specimen6_carbon = xlsread('CFRP
final.xlsx',sheet_6_carbon,xlRange_Specimen6_carbon);

figure;
plot(subset_Specimen1_carbon(:,1),subset_Specimen1_carbon(:,2));
xlabel(['\fontsize{25}Displacement (mm)'])
ylabel(['\fontsize{25}Force (N)'])
title(['\fontsize{24}CFRP: Sample 1 (12 layers)'])
figure;
plot(subset_Specimen2_carbon(:,1),subset_Specimen2_carbon(:,2));
xlabel(['\fontsize{25}Displacement (mm)'])
ylabel(['\fontsize{25}Force (N)'])
title(['\fontsize{24}CFRP: Sample 2 (12 layers)'])
figure;
```

```
plot(subset_Specimen2_carbon(:,1),subset_Specimen2_carbon(:,2));
xlabel(['\fontsize{25}Displacement (mm)'])
ylabel(['\fontsize{25}Force (N)'])
title(['\fontsize{24}Carbon-fiber sample'])
figure;
plot(subset_Specimen3_carbon(:,1),subset_Specimen3_carbon(:,2));
xlabel(['\fontsize{25}Displacement (mm)'])
ylabel(['\fontsize{25}Force (N)'])
title(['\fontsize{24}CFRP: Sample 3 (12 layers)'])
figure;
plot(subset_Specimen4_carbon(:,1),subset_Specimen4_carbon(:,2));
xlabel(['\fontsize{25}Displacement (mm)'])
ylabel(['\fontsize{25}Force (N)'])
title(['\fontsize{24}CFRP: Sample 4 (6 layers)'])
figure;
plot(subset_Specimen5_carbon(:,1),subset_Specimen5_carbon(:,2));
xlabel(['\fontsize{25}Displacement (mm)'])
ylabel(['\fontsize{25}Force (N)'])
title(['\fontsize{24}CFRP: Sample 5 (6 layers)'])
figure;
plot(subset_Specimen6_carbon(:,1),subset_Specimen6_carbon(:,2));
xlabel(['\fontsize{25}Displacement (mm)'])
ylabel(['\fontsize{25}Force (N)'])
title(['\fontsize{24}CFRP: Sample 6 (6 layers)'])

figure;
plot(subset_Specimen1_carbon(:,1),subset_Specimen1_carbon(:,2));
hold on
plot(subset_Specimen2_carbon(:,1),subset_Specimen2_carbon(:,2))
plot(subset_Specimen3_carbon(:,1),subset_Specimen3_carbon(:,2))
xlabel(['\fontsize{25}Displacement (mm)'])
ylabel(['\fontsize{25}Force (N)'])
title(['\fontsize{24}CFRP: All samples (12 layers)'])


figure;
plot(subset_Specimen4_carbon(:,1),subset_Specimen4_carbon(:,2));
hold on
plot(subset_Specimen5_carbon(:,1),subset_Specimen5_carbon(:,2))
plot(subset_Specimen6_carbon(:,1),subset_Specimen6_carbon(:,2))
xlabel(['\fontsize{25}Displacement (mm)'])
ylabel(['\fontsize{25}Force (N)'])
title(['\fontsize{24}CFRP: All samples (6 layers)'])

figure;
plot(subset_Specimen1_carbon(:,1),subset_Specimen1_carbon(:,2));
hold on
plot(subset_Specimen2_carbon(:,1),subset_Specimen2_carbon(:,2))
plot(subset_Specimen3_carbon(:,1),subset_Specimen3_carbon(:,2))
plot(subset_Specimen4_carbon(:,1),subset_Specimen4_carbon(:,2))
plot(subset_Specimen5_carbon(:,1),subset_Specimen5_carbon(:,2))
plot(subset_Specimen6_carbon(:,1),subset_Specimen6_carbon(:,2))
xlabel(['\fontsize{25}Displacement (mm)'])
ylabel(['\fontsize{25}Force (N)'])
title(['\fontsize{24}CFRP: All samples'])
```

```
%% All samples

figure;
plot(subset_Specimen3_glass(:,1),subset_Specimen3_glass(:,2));
hold on
plot(subset_Specimen4_glass(:,1),subset_Specimen4_glass(:,2))
plot(subset_Specimen2_carbon(:,1),subset_Specimen2_carbon(:,2))
plot(subset_Specimen5_carbon(:,1),subset_Specimen5_carbon(:,2))
xlabel(['\fontsize{25}Displacement (mm)'])
ylabel(['\fontsize{25}Force (N)'])
title(['\fontsize{24} Carbon-fiber vs Glass-fiber'])

%% Experimental vs model results

CFRE_12 = 'Hoja 1';
xlRange_Specimen1_CFRE12 = 'B5:E6'; %1st column: Displacement, 2nd
column: Force
subset_Specimen1_CFRE12 = xlsread('Experimental vs model
results.xlsx',xlRange_Specimen1_CFRE12);
CFRE_6 = 'Hoja 1';
xlRange_Specimen2_CFRE6 = 'F5:I6'; %1st column: Displacement, 2nd
column: Force
subset_Specimen2_CFRE6 = xlsread('Experimental vs model
results.xlsx',xlRange_Specimen2_CFRE6);
GFRE_12 = 'Hoja 1';
xlRange_Specimen3_GFRE12 = 'J5:M6'; %1st column: Displacement, 2nd
column: Force
subset_Specimen3_GFRE12 = xlsread('Experimental vs model
results.xlsx',xlRange_Specimen3_GFRE12);
GFRE_6 = 'Hoja 1';
xlRange_Specimen4_GFRE6 = 'N5:Q6'; %1st column: Displacement, 2nd
column: Force
subset_Specimen4_GFRE6 = xlsread('Experimental vs model
results.xlsx',xlRange_Specimen4_GFRE6);

figure;
plot(subset_Specimen1_CFRE12(:,1),subset_Specimen1_CFRE12(:,2));
hold on
plot(subset_Specimen1_CFRE12(:,3),subset_Specimen1_CFRE12(:,4));
xlabel(['\fontsize{25}Displacement (mm)'])
ylabel(['\fontsize{25}Force (N)'])
title(['\fontsize{24} CFRE (12 layers)'])

figure;
plot(subset_Specimen2_CFRE6(:,1),subset_Specimen2_CFRE6(:,2));
hold on
plot(subset_Specimen2_CFRE6(:,3),subset_Specimen2_CFRE6(:,4));
xlabel(['\fontsize{25}Displacement (mm)'])
ylabel(['\fontsize{25}Force (N)'])
title(['\fontsize{24} CFRE (6 layers)'])

figure;
plot(subset_Specimen3_GFRE12 (:,1),subset_Specimen3_GFRE12 (:,2));
hold on
```

```
plot(subset_Specimen3_GFRE12 (:,3),subset_Specimen3_GFRE12 (:,4));
xlabel(['\fontsize{25}Displacement (mm)'])
ylabel(['\fontsize{25}Force (N)'])
title(['\fontsize{24} GFRE (12 layers)'])

figure;
plot(subset_Specimen4_GFRE6 (:,1),subset_Specimen4_GFRE6 (:,2));
hold on
plot(subset_Specimen4_GFRE6 (:,3),subset_Specimen4_GFRE6 (:,4));
xlabel(['\fontsize{25}Displacement (mm)'])
ylabel(['\fontsize{25}Force (N)'])
title(['\fontsize{24} GFRE (6 layers)'])

figure;
plot(subset_Specimen1_CFRE12(:,1),subset_Specimen1_CFRE12(:,2));
hold on
plot(subset_Specimen1_CFRE12(:,3),subset_Specimen1_CFRE12(:,4));
plot(subset_Specimen2_CFRE6(:,1),subset_Specimen2_CFRE6(:,2));
plot(subset_Specimen2_CFRE6(:,3),subset_Specimen2_CFRE6(:,4));
plot(subset_Specimen3_GFRE12 (:,1),subset_Specimen3_GFRE12 (:,2));
plot(subset_Specimen3_GFRE12 (:,3),subset_Specimen3_GFRE12 (:,4));
plot(subset_Specimen4_GFRE6 (:,1),subset_Specimen4_GFRE6 (:,2));
plot(subset_Specimen4_GFRE6 (:,3),subset_Specimen4_GFRE6 (:,4));
xlabel(['\fontsize{25}Displacement (mm)'])
ylabel(['\fontsize{25}Force (N)'])
title(['\fontsize{24}Experimental results vs model results'])
```

APPENDIX C. ADDITIONAL FIGURES

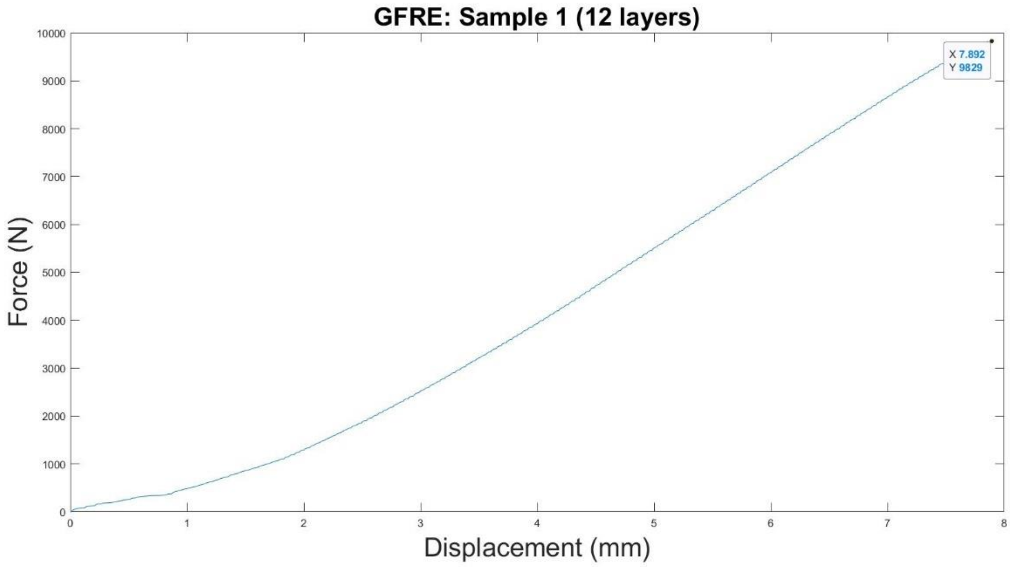


Figure C.1: Force-Displacement curve for a 12 layers sample of GFRE

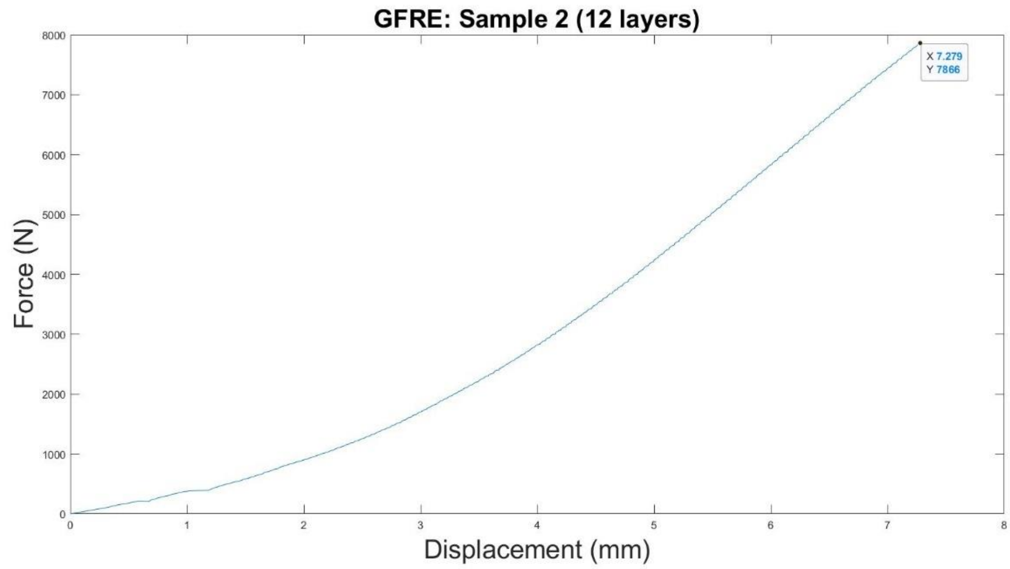


Figure C.2: Force-Displacement curve for a 12 layers sample of GFRE

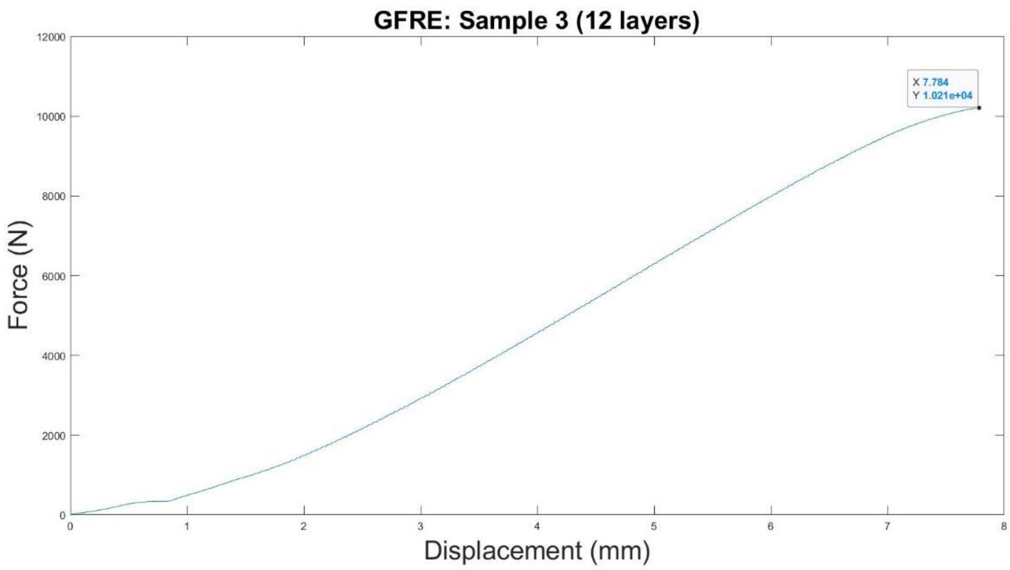


Figure C.3: Force-Displacement curve for a 12 layers sample of GFRE

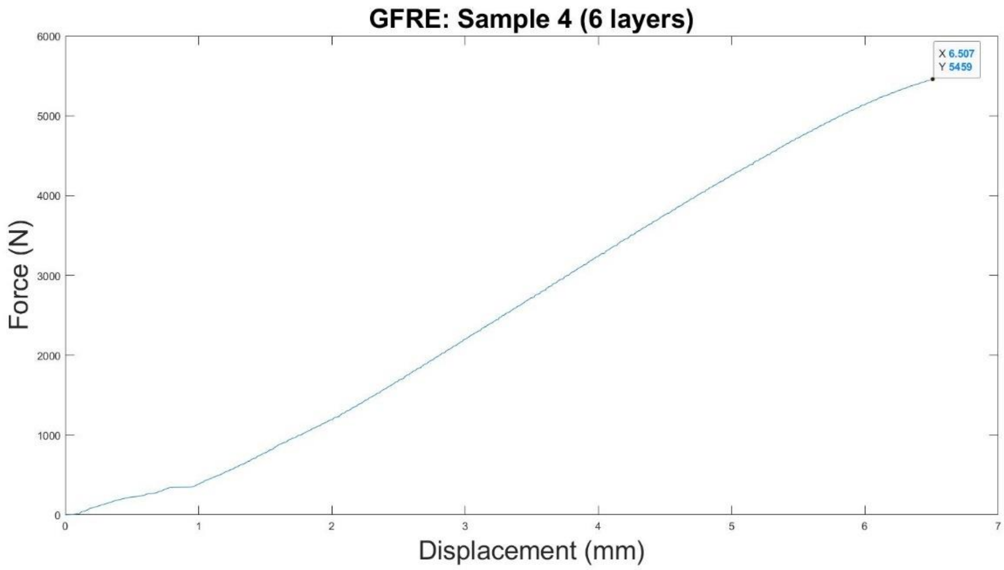


Figure C.4: Force-Displacement curve for a 6 layers sample of GFRE

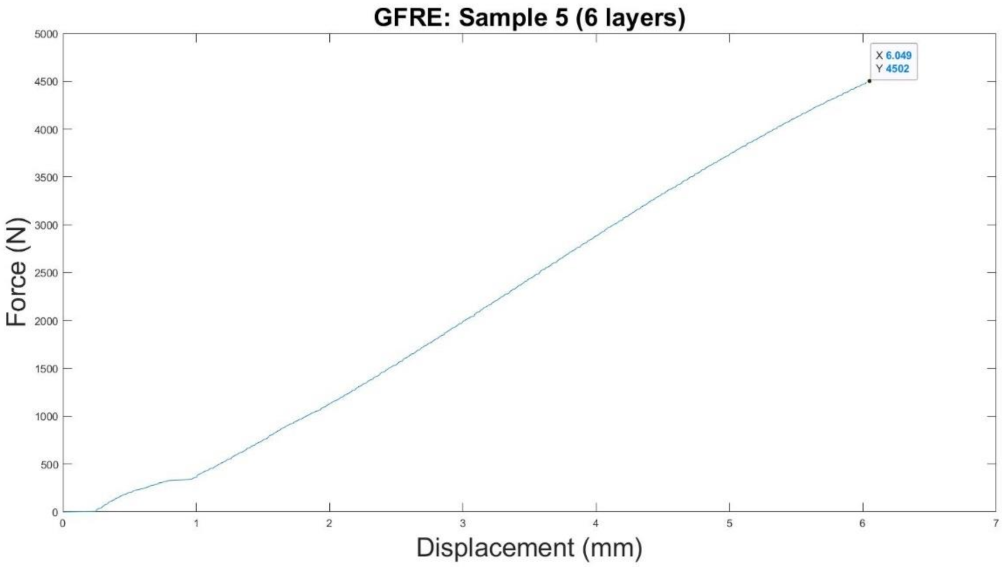


Figure C.5: Force-Displacement curve for a 6 layers sample of GFRE

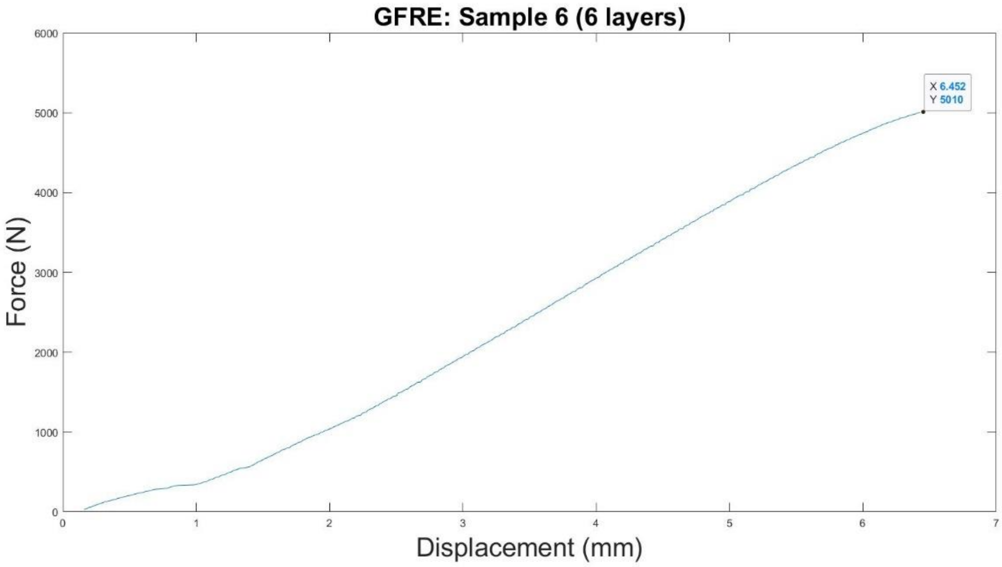


Figure C.6: Force-Displacement curve for a 6 layers sample of GFRE

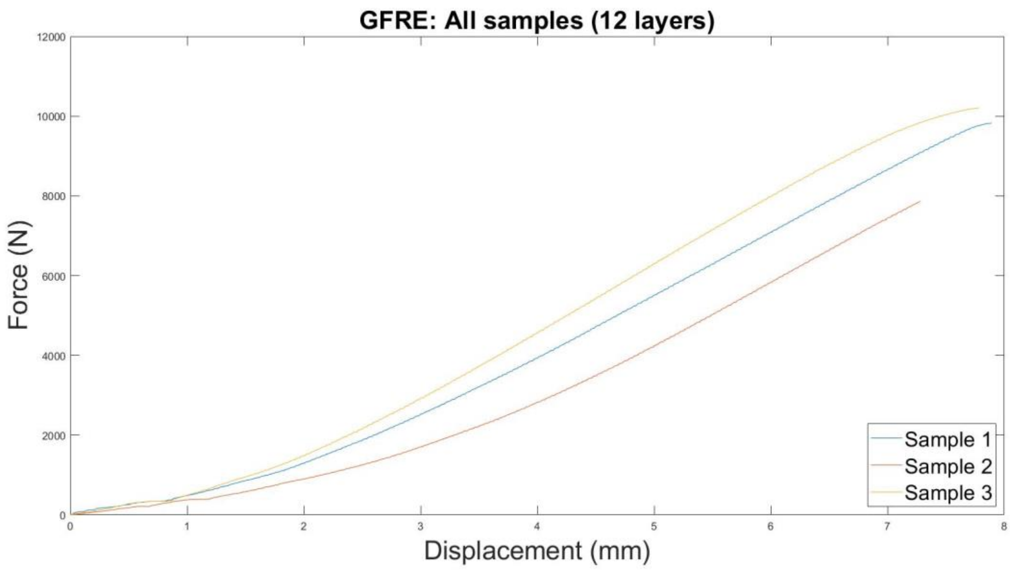


Figure C.7: Force-Displacement curve for all 12 layers samples of GFRE

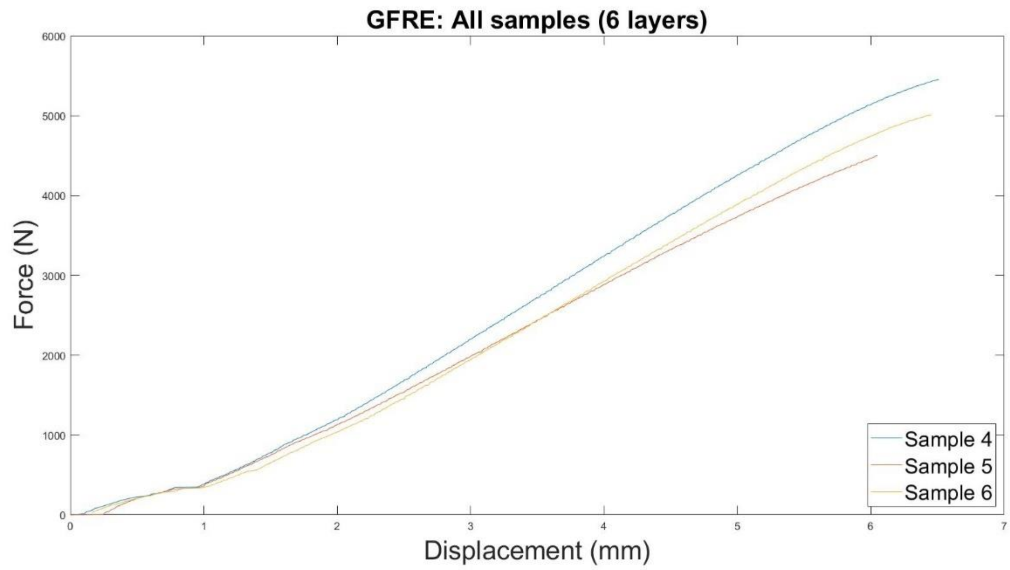


Figure C.8: Force-Displacement curve for all 6 layers samples of GFRE

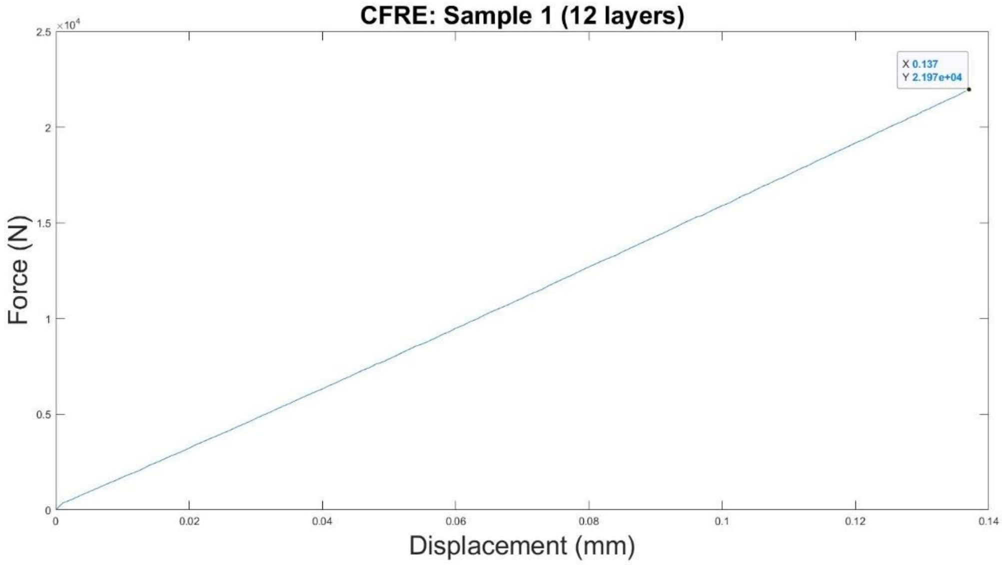


Figure C.9: Force-Displacement curve for a 12 layers sample of CFRE

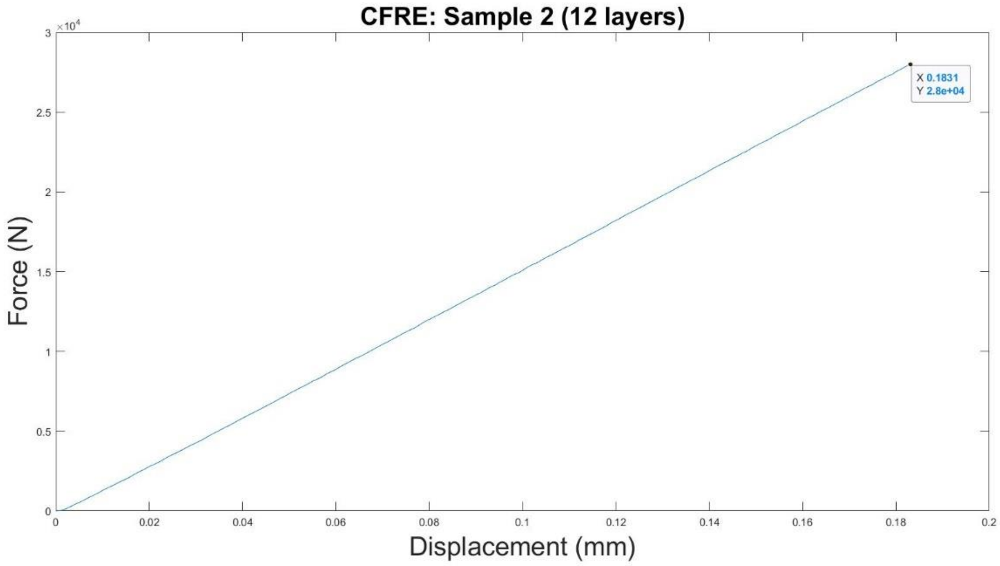


Figure C.10: Force-Displacement curve for a 12 layers sample of CFRE

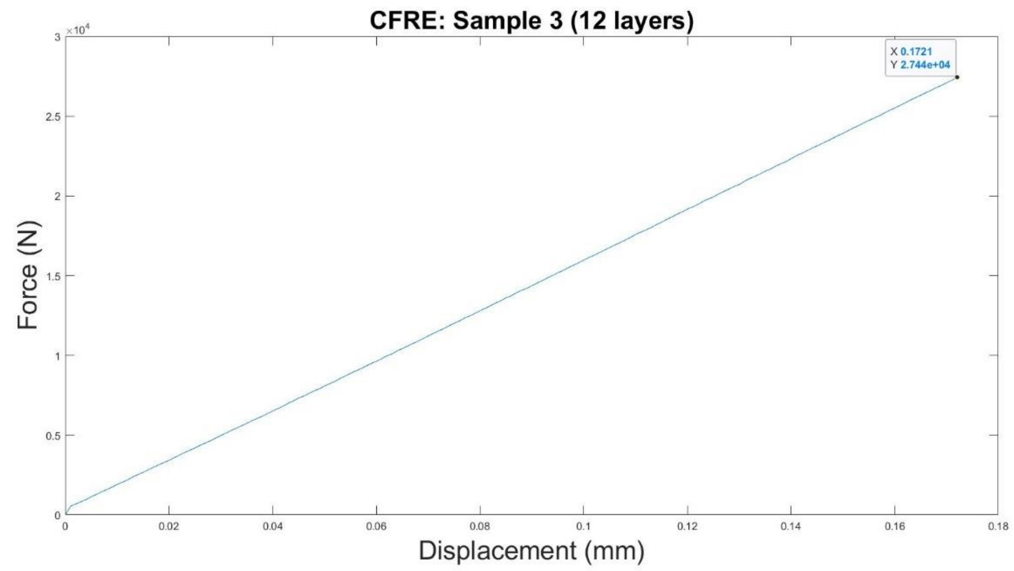


Figure C.11: Force-Displacement curve for a 12 layers sample of CFRE

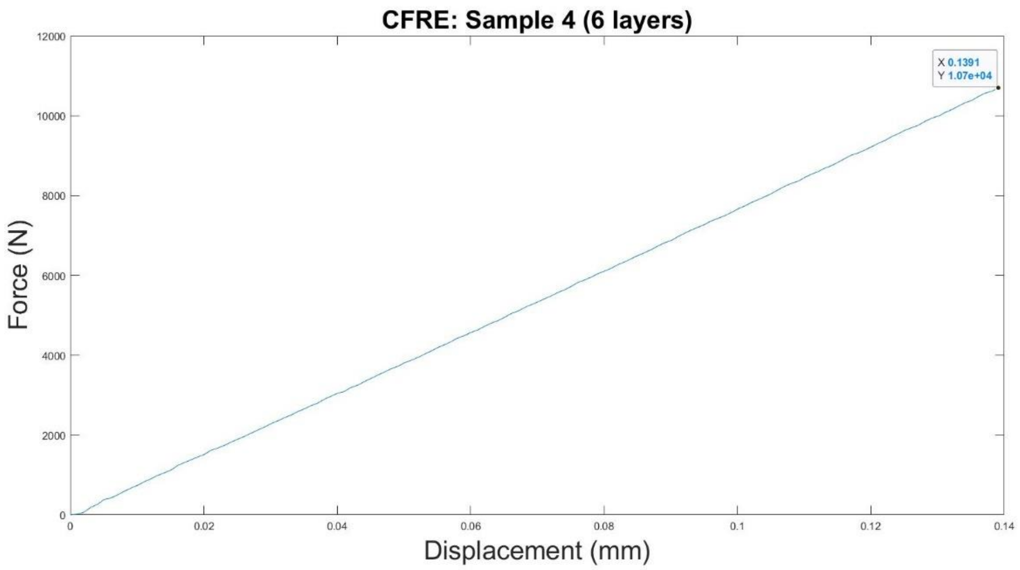


Figure C.12: Force-Displacement curve for a 6 layers sample of CFRE

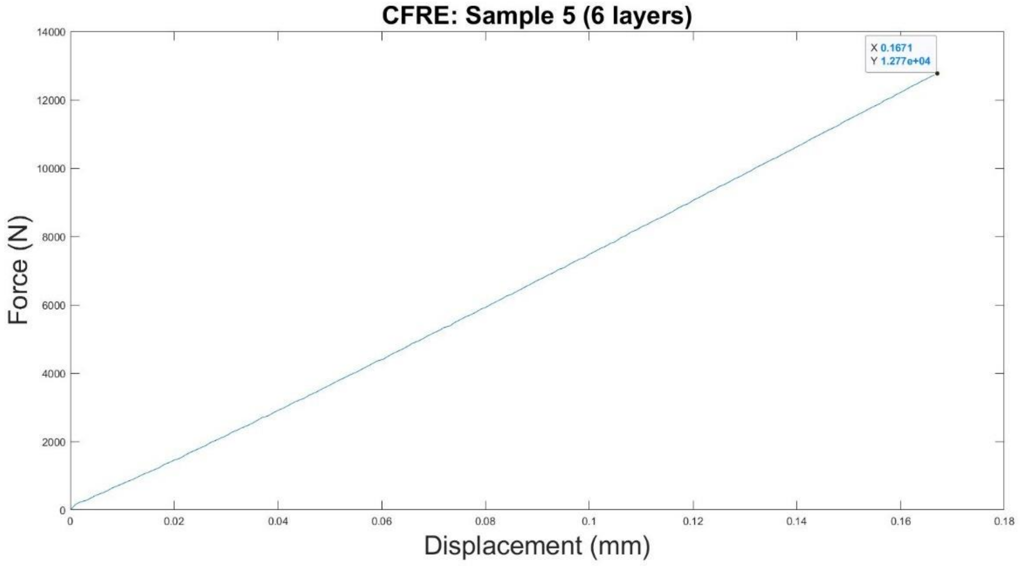


Figure C.13: Force-Displacement curve for a 6 layers sample of CFRE

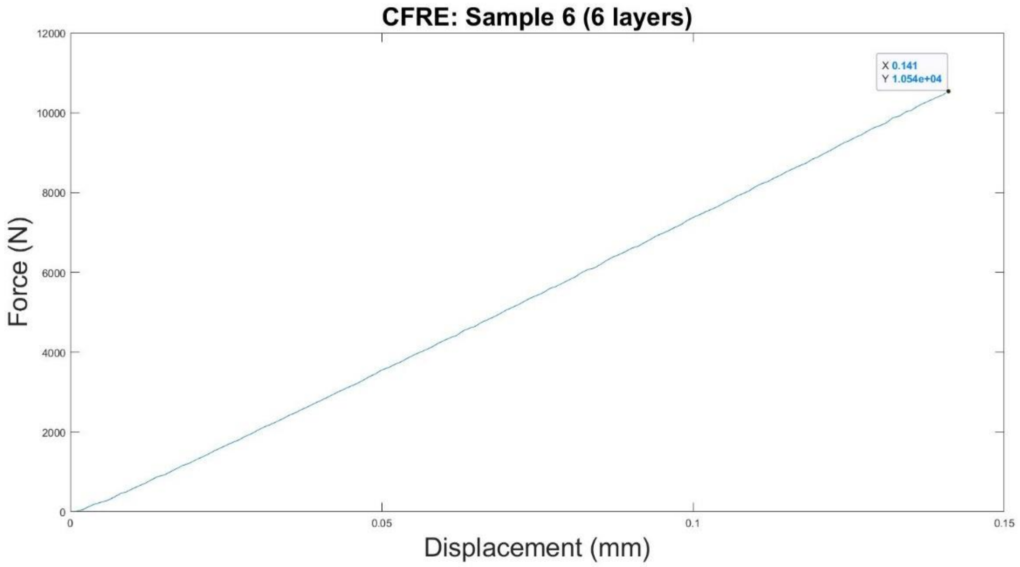


Figure C.14: Force-Displacement curve for a 6 layers sample of CFRE

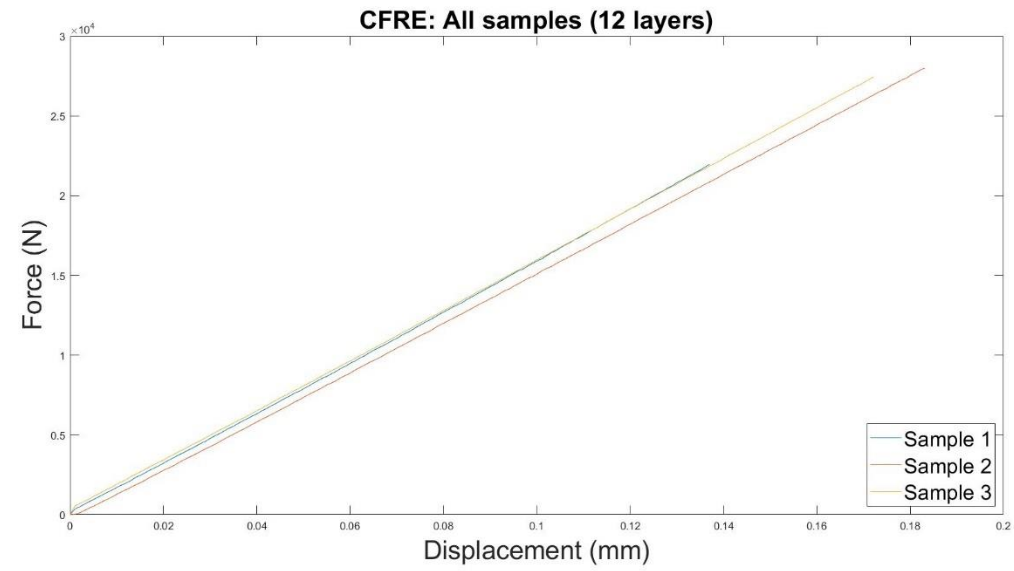


Figure C.15: Force-Displacement curve for all 12 layers samples of CFRE

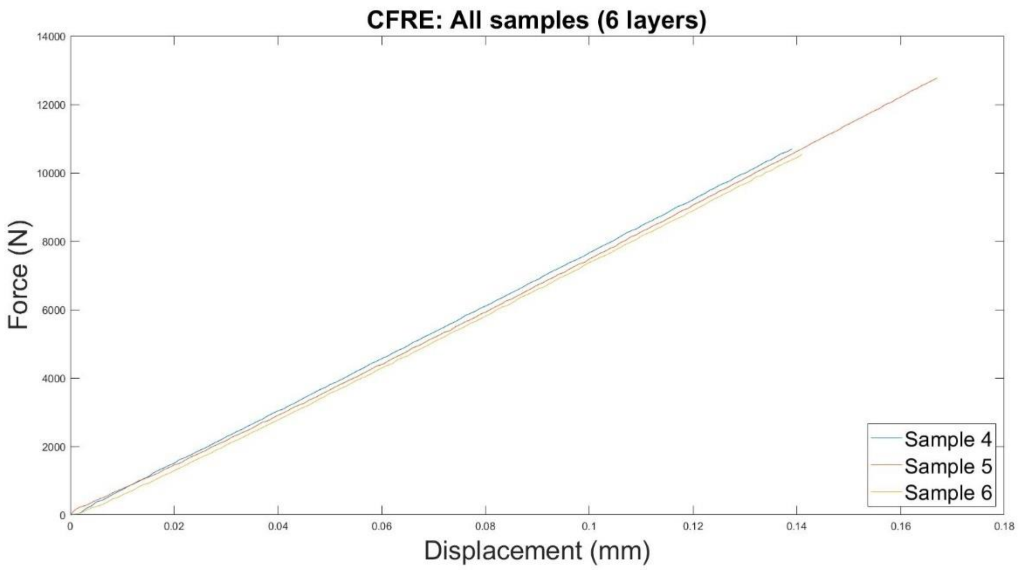


Figure C.16: Force-Displacement curve for all 6 layers samples of CFRE

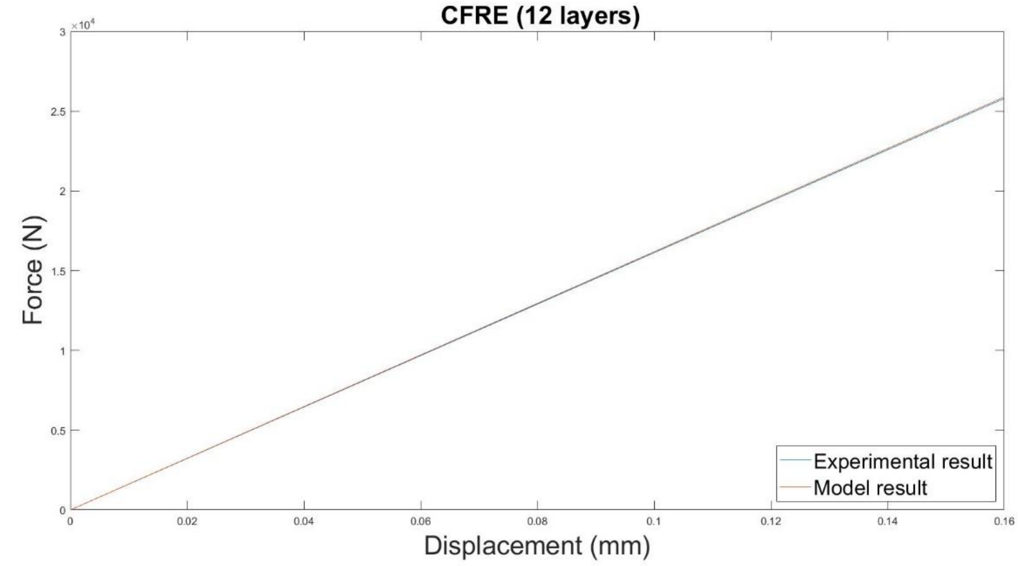


Figure C.17: Experimental result vs model result of a 12 layers sample of CFRE

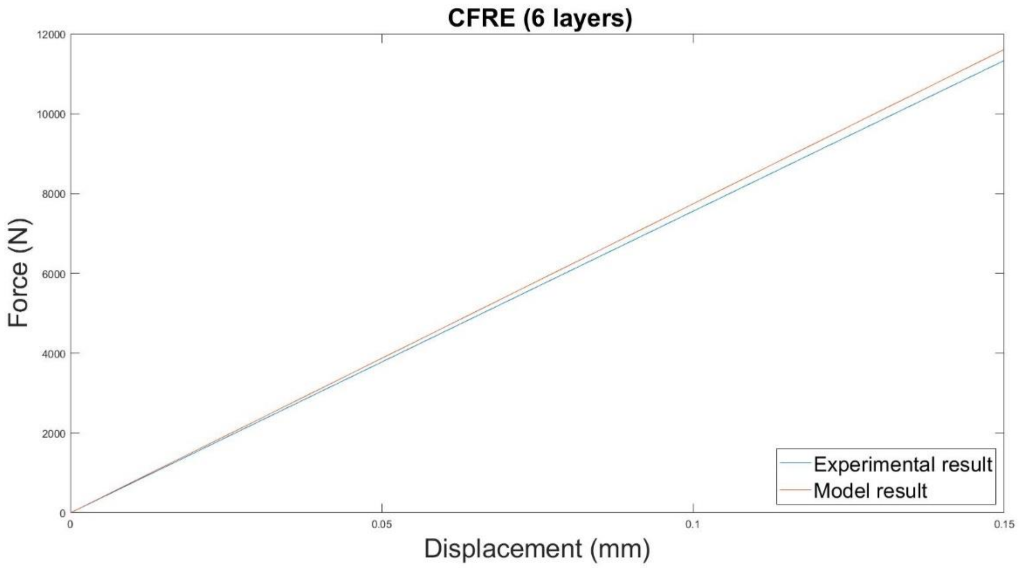


Figure C.18: Experimental result vs model result of a 6 layers sample of CFRE

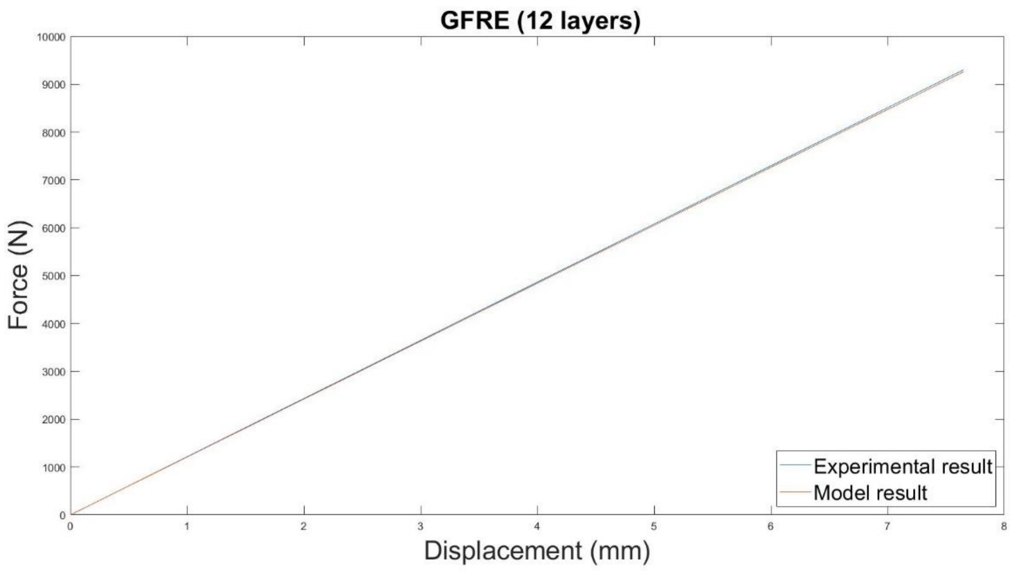


Figure C.19: Experimental result vs model result of a 12 layers sample of GFRE

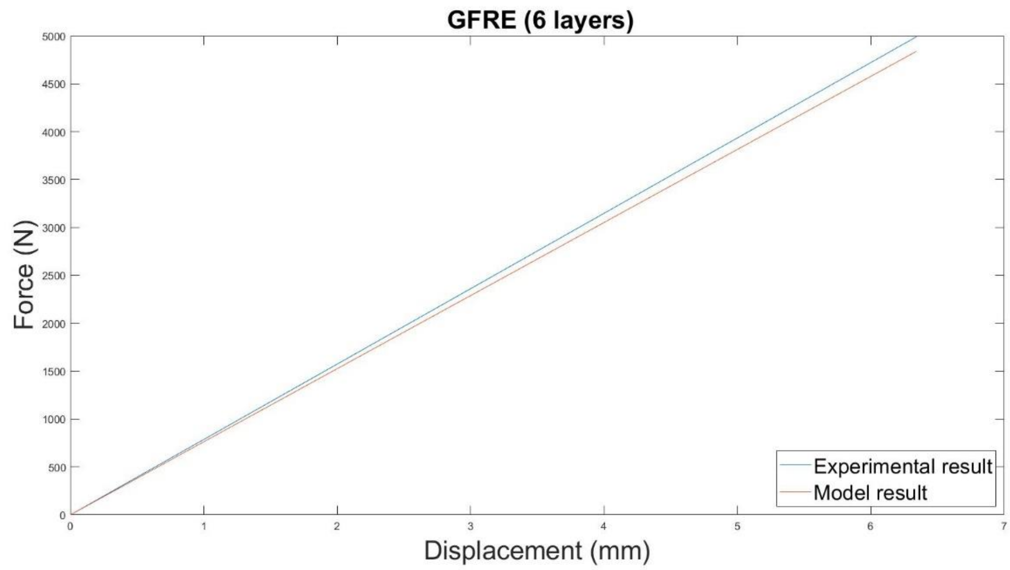


Figure C.20: Experimental result vs model result of a 6 layers sample of GFRE

APPENDIX D. HANDS-ON ACTIVITY

MATERIALS SCIENCE & TECHNOLOGY (CTM)

HANDS-ON ACTIVITY ON FABRICATION AND TESTING OF COMPOSITES STATEMENT OF WORK (SoW)

Through this hands-on activity the students will learn the following:

- First, the students will recall the theoretical knowledge on materials' properties that they acquired in the frame of CTM.
- They will also learn how to fabricate composites through the hand-layup technique, which is the most appropriate technique according to the resources of the School.
- Finally, the students will learn the basis of the operation of a Universal Testing Machine (UTM) by testing different samples several times.

a) Activities to be performed before the laboratory session:

1- Check several tutorials on YouTube to learn how to handle the glass fibers and carbon fibers, since they move very easily and sometimes it is necessary to use some tricks to obtain an acceptable result.[1]
2- Check several tutorials on YouTube to learn how to use the UTM and get informed about the uses of this machine. [2]
3- Take a look at all the documentation provided in the CTM theory classes to refresh the basic knowledge about composites and their mechanical properties.

b) Activities to be performed while in the laboratory:

1- Fabrication of composites.
2- Analysis of mechanical properties using UTM.

c) Activities to be performed after the laboratory session (homework):

1- Theoretical questions:

a. Identify the parts of the composite and describe their main characteristics.

[1] https://www.youtube.com/watch?v=IAdVO8Rkv6c
https://www.youtube.com/watch?v=EhAvCqtIo7w
[2] https://www.youtube.com/watch?v=ekO-2MZiCIQ
https://www.youtube.com/watch?v=aH9vcV7jzG0

b. What is the purpose of the resin in composite materials with long fibers at high concentrations?
c. Identify three advantages of composite materials over metals for structural applications.
   Which of the following stacking sequences is the most appropriate to obtain the best mechanical properties for a composite of 6 layers? Justify your answer.

a)	b)	c)	d)	e)
45/135	0/90	45/135	45/135	0/90
0/90	0/90	0/90	45/135	45/135
0/90	0/90	45/135	45/135	0/90
0/90	0/90	0/90	45/135	45/135
0/90	0/90	45/135	45/135	0/90
45/135	0/90	0/90	45/135	45/135

d. Which of the following stacking sequences is the most appropriate to obtain the best mechanical properties for a composite of 12 layers? Justify your answer.

a)	b)	c)	d)	e)
45/135	45/135	45/135	0/90	45/135
0/90	45/135	0/90	0/90	0/90
45/135	45/135	0/90	0/90	0/90
0/90	45/135	0/90	0/90	0/90
45/135	45/135	0/90	0/90	45/135
45/135	45/135	45/135	0/90	45/135
45/135	0/90	45/135	0/90	45/135
0/90	0/90	0/90	0/90	0/90
45/135	0/90	0/90	0/90	0/90
0/90	0/90	0/90	0/90	0/90
45/135	0/90	0/90	0/90	0/90
45/135	0/90	45/135	0/90	45/135

e. Indicate three reasons why epoxies are the resins of choice in making composite parts for airplane structures such as wing and tail components.
f. Explain an advantage of spray-up over lay-up? Explain an advantage of lay-up over spray-up?

2- **Problem:** In the design of a specimen made of composite material, we must study the material more suitable for the fiber. The size of this specimen is 226x25,40x2,70 mm and its initial length is 18 cm. The matrix material is epoxy resin, with a Young's modulus of 3,4 GPa, a yield stress of 25 MPa and an ultimate tensile strength of 50 MPa. This material is elastically deformed applying a force of 5 kN.

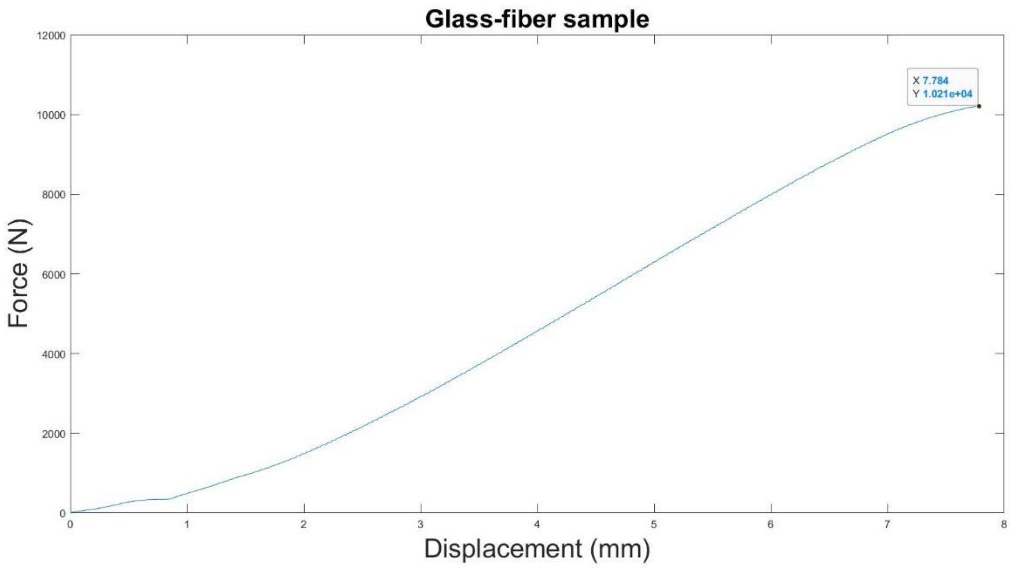
Assume that both volume fraction of matrix and fibers is 50%, you are asked to calculate:

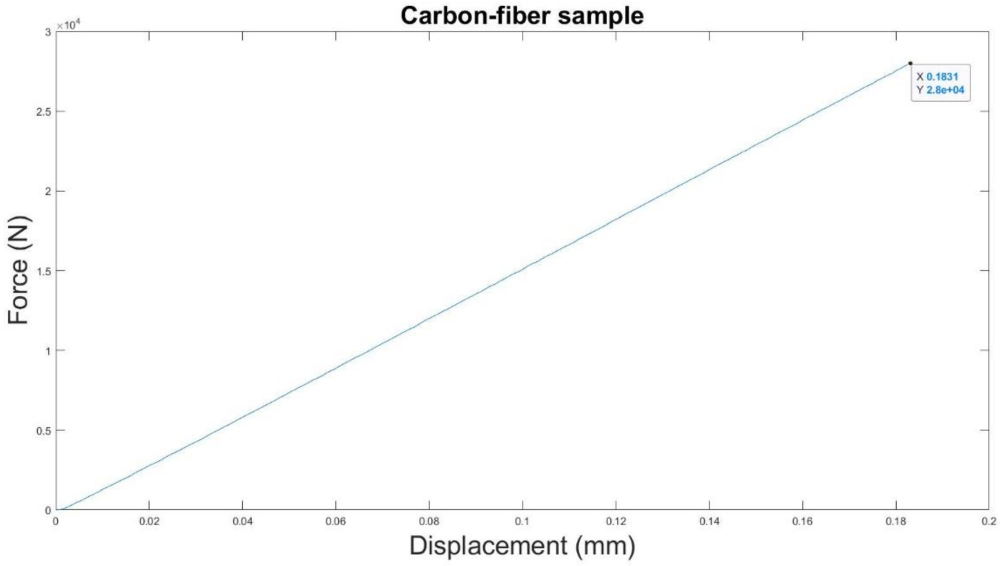
a. Calculate the Young's modulus of the composite.
b. Check that the composite does not exceed its yield stress for the applied force.
c. Calculate the deformation of the composite, matrix and reinforcement.
d. Calculate the stress carried by the fibers.

The following data can be used to solve these problems:

	Young's modulus (GPa)	**Yield stress (MPa)**
Glass	70,00	150,00
Carbon	320,00	370,00

3- Problem: In the design of a specimen made of composite material, we must study the material more suitable for the fiber. The size of this specimen is 226×25,4×2,70 mm and its initial length is 18 cm. This material is elastically deformed applying its maximum possible load. Assume that both volume fraction of matrix and fibers is 50% and using the data provided by the graphic below, calculate:





	Force (N)	Displacement (mm)
GFRE	10.210,00	7,784
CFRE	28.000,00	0,1831

a. Total deformation of the composite.
b. Stress carried by the composite.
c. Young's modulus of the composite.

RESOLUTION

1- Answers to theoretical questions:

a) A composite material is formed by the matrix and the reinforcement:

- Matrix → The matrix is the continuous phase. Its principal role is to give shape to the composite part, to protect the reinforcement from the environment, to transfers loads to the reinforcement, and to contribute to properties that depend upon both the matrix and the reinforcement, such as the fracture toughness
- Reinforcement → The reinforcement gives strength, stiffness, and other properties to the composite. Reinforcements as fibers are the most important and have the largest effect on composite properties.

b) When the composite is made of long fibers at high concentrations, and especially if they have high mechanical properties, the fibers dominate the properties of the composite structure. The main role of the matrix for this type of composites is its high thermal and protective capabilities in order to protect the fibers from the environment.

c) 1. Composites are lighter than metals.
2. Composites are incredibly stronger than metals.
3. Composites are more corrosion resistant than metals.

d) a) → Correct answer. It has fibers oriented in different directions in order to give strength to the part and there is symmetry.
b) → It is not possible because composites cannot have all the fibers oriented in the same direction.
c) → It is not possible because there is no symmetry with respect to the mid-plane.
d) → It is not possible because composites cannot have all the fibers oriented in the same direction.
e) → It is not possible because there is no symmetry with respect to the mid-plane.

e) a) → It is not possible because there is no symmetry with respect to the mid-plane.
b) → It is not possible because there is no symmetry with respect to the mid-plane.
c) → Correct answer. It has fibers oriented on different directions in order to give strength to the part and there is symmetry.

d) → It is not possible because composites cannot have all the fibers oriented in the same direction.
e) → It is not possible because there is no symmetry with respect to the mid-plane.

f) 1. The excellent balance between good properties and moderate cost.
2. Strength and stiffness are superior for epoxies.
3. Creep resistance is superior for epoxies.

g) The advantage of spray-up over lay-up for most parts is simply the speed with which the fiber and the resin can be applied to the mold. On the other hand, the advantage of lay-up over spray-up is that lay-up does not need special equipment, it allows using a wide range of fibers, the orientation of the fibers can be controlled, and there is no need of a highly-skilled operator.

2- **Results**:

a) The Young's modulus of the composite can be calculated as follows:

$$\textbf{Glass}: \quad \boldsymbol{E} = V_f E_f + V_m E = 0{,}5 \cdot 70 \cdot 10^9 + 0{,}5 \cdot 3{,}4 \cdot 10^9 = \mathbf{36{,}70}\ \boldsymbol{GPa}$$
$$\textbf{Carbon}: \quad \boldsymbol{E} = V_f E_f + V_m E = 0{,}5 \cdot 320 \cdot 10^9 + 0{,}5 \cdot 3{,}4 \cdot 10^9 = \mathbf{161{,}70}\ \boldsymbol{GPa}$$

b) We compare the stress corresponding to the applied force and the yield stress:

Stress corresponding to 5 kN:

$$\boldsymbol{\sigma} = \frac{\boldsymbol{F}}{\boldsymbol{A}} = \frac{\mathbf{5 \cdot 10^3}}{\mathbf{68{,}58}} \rightarrow \ \mathbf{72{,}91}\ \boldsymbol{MPa}$$

Maximum stress of the composites without experiencing plastic deformation:

$$\textbf{Glass}: \quad \boldsymbol{\sigma_y} = 150\ \boldsymbol{MPa}$$
$$\textbf{Carbon}: \quad \boldsymbol{\sigma_y} = 370\ \boldsymbol{MPa}$$

As can be noticed, the stress experienced by the composites when applying a force of 5 kN is lower than both yield stress values, so the materials will not experience plastic deformation when applying a force of 5 kN. Moreover, as the yield stress can be considered the upper limit of the elastic deformation region in the stress-strain curves of the composites, the Hooke's law can be applied to obtain the deformation of the composite, and its fibers and matrix.

c) Deformation of the composite, and its fibers and matrix:

$$\textbf{Glass}: \qquad \boldsymbol{\varepsilon} = \frac{\sigma}{E} = \frac{72{,}91\ MPa}{36{,}70\ GPa} \cdot 100 = \mathbf{0,20}\%$$

$$\textbf{Carbon}: \qquad \boldsymbol{\varepsilon} = \frac{\sigma}{E} = \frac{72{,}91\ MPa}{161{,}70\ \ GPa} \cdot 100 = \mathbf{0,045}\%$$

d) As mentioned, the deformation of the fibers is the same as that of the matrix and composite. Again, applying Hooke's Law, we can obtain the stress that the fibers are carrying for the computed deformation:

$$\textbf{Glass}: \quad \boldsymbol{\sigma} = E \cdot \varepsilon = 70 \cdot 10^9 \cdot 0{,}002 = \mathbf{140}\ \boldsymbol{MPa}$$
$$\textbf{Carbon}: \quad \boldsymbol{\sigma} = E \cdot \varepsilon = 320 \cdot 10^9 \cdot 0{,}00045 = \mathbf{144}\ \boldsymbol{MPa}$$

3- **Results:**

a) In this case, the strain of the composite can be calculated using the data provided by the different plots and the data given in the statement of work:

$$\textbf{Glass}: \qquad \boldsymbol{\varepsilon} = \frac{\Delta L}{L_0} = \frac{7{,}784}{180} = 0{,}0432 = \mathbf{4,32}\%$$

$$\textbf{Carbon}: \qquad \boldsymbol{\varepsilon} = \frac{\Delta L}{L_0} = \frac{0{,}1831}{180} = 0{,}001 = \mathbf{0,10}\%$$

As for any composite, the total deformation of the composite is equal to that of the fibers and the matrix.

b) The total stress that the composite is carrying can be calculated as follows:

$$\textbf{Glass}: \qquad \boldsymbol{\sigma} = \frac{F}{A} = \frac{10.210}{68{,}58} = \mathbf{148,88}\ \boldsymbol{MPa}$$

$$\textbf{Carbon}: \qquad \boldsymbol{\sigma} = \frac{F}{A} = \frac{28.000}{68{,}58} = \mathbf{408,28}\ \boldsymbol{MPa}$$

c) The Young's modulus of the composite is calculated with the slope of the graphics.

For the glass fibers, we choose two different points of the linear part of the curve and we calculate the corresponding stress and strain. For example, the first point (4 mm, 4.500 N) and the second point (5 mm, 6.300 N).

$$\textbf{Glass}: \quad \boldsymbol{E} = \frac{\sigma_2 - \sigma_1}{\varepsilon_2 - \varepsilon_1} = \frac{\frac{F_2}{A} - \frac{F_1}{A}}{\frac{\Delta L_2}{L_0} - \frac{\Delta L_1}{L_0}} = \frac{\frac{6.300}{68{,}58} - \frac{4.500}{68{,}58}}{\frac{5}{180} - \frac{4}{180}} = \boldsymbol{4{,}72\ GPa}$$

For the carbon fibers, we have to follow the same procedure as with the glass fibers, but the curve is completely linear, so using the points (0,0) and the maximum point provided in the problem statement, it can be calculated as follows:

$$\textbf{Carbon}: \quad \boldsymbol{E} = \frac{\sigma_2 - \sigma_1}{\varepsilon_2 - \varepsilon_1} = \frac{408{,}28 - 0}{0{,}001 - 0} = \boldsymbol{408{,}28\ GPa}$$